PB-238 355

ESTIMATING NUTRIENT LOADINGS OF LAKES FROM NON-POINT SOURCES

WISCONSIN UNIVERSITY

PREPARED FOR
NATIONAL ENVIRONMENTAL RESEARCH CENTER

AUGUST 1974

DISTRIBUTED BY:
NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

1. Report No.
2.
3. Accession No.

PB 238 355

4. Title

ESTIMATING NUTRIENT LOADINGS OF LAKES FROM NON-POINT SOURCES,

5. Report Date
6.
8. Performing Organization Report No.

7. Author(s)

Uttormark, P. D., Chapin, J. D., and Green, K. M.

10. Project No.

Wisconsin Univ., Madison. Water Resources Center.

11. Contract/Grant No.

R-801343

12. Sponsoring Organization

13. Type of Report and Period Covered

15. Supplementary Notes

Environmental Protection Agency report number, EPA-660/3-74-020, August 1974

16. Abstract

Data describing nutrient contributions from non-point sources were compiled from the literature, converted to kg/ha/yr, and tabulated in a format convenient for estimating nutrient loadings of lakes. Contributing areas are subdivided according to general use categories, including agricultural, urban, forested, and wetland. Data describing nutrient transport by groundwater seepage and bulk precipitation are given along with data for nutrient contributions from manure handling, septic tanks, and agricultural fertilizers. Nutrient content of urban runoff was the highest; forested areas were lowest. Nutrient export data for agricultural lands were tabulated as seepage through vertical soil profile, overland runoff, and transport by streams draining agricultural watersheds. The latter group was judged to be most applicable for estimating nutrient loading of lakes. Marshes appear to temporarily store phosphorus and nitrogen during the growing season and release them at a later time; net nutrient runoff is estimated to be near zero. Nutrient contributions to lakes from groundwater seepage require site-specific information for assessment. Phosphorus and nitrogen transport by groundwater can be significant. Atmospheric contributions of nitrogen are large in some areas. The technique of estimating nutrient loadings of lakes requires considerable judgement in selecting runoff coefficients; however, the approach provides insight into potential management options. (Uttormark-Wisconsin)

17a. Descriptors

*Nutrients, *Eutrophication, *Control, Management, Drainage, Nitrogen, Phosphorus, Agriculture, Estimating, Chemical properties, Runoff, Groundwater, Fallout, Sewage, Precipitation (Atmospheric), Seepage, Urban runoff, Forests, Marshes, Wetlands, Septic tanks.

17b. Identifiers

*Lake management, Nutrient load, Nutrient sources.

17c. COWRR Field & Group

05C

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
US Department of Commerce
Springfield, VA. 22151

PRICES SUBJECT TO CHANGE

18. Availability

19. Security Class. (Report)

20. Security Class. (Page)

21. No. of Pages

121

22. Price

$3.90/2.25

Send To:

WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

Abstractor

P. D. Uttormark

Institution

Wisconsin Univ., Madison

WRSIC 102 (REV. JUNE 1971)

GPO 480-935

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Monitoring, Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ECOLOGICAL RESEARCH series. This series describes research on the effects of pollution on humans, plant and animal species, and materials. Problems are assessed for their long- and short-term influences. Investigations include formation, transport, and pathway studies to determine the fate of pollutants and their effects. This work provides the technical basis for setting standards to minimize undesirable changes in living organisms in the aquatic, terrestrial and atmospheric environments.

EPA REVIEW NOTICE

This report has been reviewed by the Office of Research and Development, EPA, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 -

EPA-660/3-74-020
August 1974

ESTIMATING NUTRIENT LOADINGS OF LAKES FROM NON-POINT SOURCES

by

Paul D. Uttormark
John D. Chapin
Kenneth M. Green

Water Resources Center
University of Wisconsin
Madison, Wisconsin 53706

Program Element 1BA031
Roap/Task 21 AJE 28
Grant R-801343

Project Officer

Thomas E. Maloney
National Environmental Research Center
Corvallis, Oregon 97330

Prepared for

OFFICE OF RESEARCH AND MONITORING
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

ib

ABSTRACT

Data describing nutrient contributions from non-point sources were compiled from the literature, converted to kg/ha/yr, and tabulated in a format convenient for estimating nutrient loadings of lakes. Contributing areas are subdivided according to general use categories, including agricultural, urban, forested, and wetland. Data describing nutrient transport by groundwater seepage and bulk precipitation are given along with data for nutrient contributions from manure handling, septic tanks, and agricultural fertilizers.

Nutrient content of urban runoff was the highest; forested areas were lowest. Nutrient export data for agricultural lands were tabulated as: seepage through vertical soil profile, overland runoff, and transport by streams draining agricultural watersheds. The latter group was judged to be most applicable for estimating nutrient loadings of lakes. Marshes appear to temporarily store phosphorus and nitrogen during the growing season and release them at a later time; net nutrient runoff is estimated to be near zero. Nutrient contributions to lakes from groundwater seepage require site-specific information for assessment. Phosphorus and nitrogen transport by groundwater can be significant. Atmospheric contributions of nitrogen are large in some areas.

The technique of estimating nutrient loadings of lakes requires considerable judgment in selecting runoff coefficients; however, the approach provides insight into potential management options.

This report was submitted in fulfillment of Grant R-801343 by the University of Wisconsin under the sponsorship of the Environmental Protection Agency. Work was completed as of June 1974.

CONTENTS

		Page
Abstract		ii
List of Figures		iv
List of Tables		v
Sections		
I	Introduction	1
II	Nutrient Sources and Transport Vectors	6
	Nutrient Sources	6
	Contributing Areas	7
III	Nutrient Export from Agricultural Lands	13
	Fertilizers	14
	Nutrient Losses by Seepage	19
	Surface Runoff from Agricultural Lands	24
	Nutrient Transport by Streams Draining Agricultural Lands	29
	Manure Handling	40
IV	Nutrient Export from Urban Areas	48
	Factors Contributing to the Nutrient Content of Urban Runoff	51
V	Nutrient Export from Forests	55
VI	Nutrient Losses from Marshes and Wetlands	60
VII	Nutrient Influx from Groundwater	62
VIII	Nutrient Contributions from Septic Tanks	71
IX	Atmospheric Contributions of Nitrogen and Phosphorus	74
	Factors Affecting Nutrient Content of Bulk Precipitation	74
	Cartographic Presentation of Nitrogen Contributions from Precipitation	78
X	Summary	100

CONTENTS

Page

Abstract ii

List of Figures iv

List of Tables v

Sections

I Introduction 1

II Nutrient Sources and Transport Vectors 6

  Nutrient Sources 6

  Contributing Areas 7

III Nutrient Export from Agricultural Lands 13

  Fertilizers 14

  Nutrient Losses by Seepage 19

  Surface Runoff from Agricultural Lands 24

  Nutrient Transport by Streams Draining Agricultural Lands 29

  Manure Handling 40

IV Nutrient Export from Urban Areas 48

  Factors Contributing to the Nutrient Content of Urban Runoff 51

V Nutrient Export from Forests 55

VI Nutrient Losses from Marshes and Wetlands 60

VII Nutrient Influx from Groundwater 62

VIII Nutrient Contributions from Septic Tanks 71

IX Atmospheric Contributions of Nitrogen and Phosphorus 74

  Factors Affecting Nutrient Content of Bulk Precipitation 74

  Cartographic Presentation of Nitrogen Contributions from Precipitation 78

X Summary 100

FIGURES

No.		Page
1	Subdivision of Drainage Basins	10
2	Nitrogen Contributions (NO_3-N & NH_4-N) from Rainfall	87
3a	Format for Comparing Nutrient Runoff Coefficients	103
3b	Nutrient Export from Urban Areas	104
3c	Nutrient Export from Forested Lands	105
3d	Nutrient Export from Agricultural Lands	106

TABLES

No.		Page
1	Specific Loading Levels for Lakes Expressed as Total Nitrogen and Total Phosphorus in $g/m^2/yr$	2
2	"Natural" Modes of Nutrient Transport to Lakes	7
3	Annual Loss of N, P, and Suspended Solids in Tile Drainage Water, Woodslee, Ontario	15
4	Nutrient Export in Surface Runoff from Experimental Plots--Sediment and Water Fractions	17
5	Effect of Crop Cover and Slope on Nutrient Export via Surface Runoff	18
6	Nutrient Export from Croplands by Seepage through Soil Profile	25
7	Nitrate Export from Croplands by Surface Runoff	30
8	Nutrient Export from Croplands by Surface Runoff	31
9	Nutrient Transport from Agricultural Watersheds by Streams	36
10	Nutrient Characteristics of Manure from Domestic Animals	41
11	Export of Nutrients from Urban Areas	49
12	Average Nutrient Concentrations in Urban Runoff	52
13	Nutrient Export from Forested Watershed via Streamflow	58
14	Nutrient Contributions to Lakes via Groundwater	63
15	Partial List of Methods for Investigating the Groundwater-Surface Water Interchange	65

16 Groundwater Contributions to the Water Budget of Lakes 66

17 Atmospheric Contributions of Nitrogen 79

18 Atmospheric Contributions of Phosphorus 83

19 Influence of Local Conditions on Nutrient Contributions from the Atmosphere 89

20 Typical Values of Nutrient Runoff Coefficients 108

21 Direct Drainage Areas for Selected Wisconsin Lakes 109

22 Conversion Factors 112

INTRODUCTION

Eutrophication is a natural process which affects lakes at different rates. Some lakes are relatively unaffected by natural factors which have been operating for thousands of years. Others have passed through advanced stages of eutrophication and are now extinct. Although eutrophication is often described as an aging process, it is important to realize that the process is not necessarily unidirectional--reversals are possible and do occur.

It has been known for years that the natural process of eutrophication can be accelerated by the activities of people. Analyses of lake sediment cores have been used to document this observation. The exact mechanisms by which the activities of people influence the rate of eutrophication have been identified only in general terms, but it is reasonable to assume that land use practices are a significant factor because they alter the pathways and rate of nutrient transport from the landscape.

Mounting concern for maintaining water quality in lakes and controlling the undesirable effects of eutrophication has emphasized the need for quantitative information concerning the nutrient budgets of lakes. It is generally agreed that the most desirable long-term lake management approach is to control, insofar as is possible, the influx of nutrients, although there is considerable disagreement regarding the selection of nutrient sources which should be controlled, the method for control, and the benefit which is to be gained. In particular, the complex internal nutrient cycles involving lake sediments have been identified as factors which could potentially negate the beneficial effects of reducing external inputs of nutrients. Nevertheless, even though a drastic reduction of the nutrient input may not alone be sufficient to attain the desired level of water quality in all instances, nutrient abatement is an essential component of management efforts. Regardless of internal nutrient cycles, water quality improvement will not result if the continuous influx of nutrients is excessive.

The intricate process of eutrophication is far too complex to expect that simple relationships can be established between the influx of nutrients and undesirable plant production or other parameters of lake quality. Yet, sufficient information does exist to provide some guidelines.

On the basis of water analyses from 17 Wisconsin lakes, Sawyer (1947) suggested that if, at time of spring overturn, concentrations of inorganic phosphorus and inorganic nitrogen (ammonia plus nitrate nitrogen) exceeded 0.01 mg/l and 0.3 mg/l respectively, a lake may be expected to produce excessive growths of algae or other aquatic plants. Vollenweider (1968) statistically analyzed data reported by Thomas (1953) and concluded that the critical levels suggested by Sawyer were generally borne out by the conditions of lakes in central Europe.

These critical concentrations, although not rigid lines of demarcation, do provide target values for lake improvement and protection. However, it is difficult to relate these values directly to reductions in nutrient input, because the relationship between nutrient influx and in-lake nutrient concentrations is poorly understood.

Tentative guidelines for relating the nutrient influx to water quality in lakes are provided by criteria presented by Vollenweider (1968). The surface area of the lake is taken into account by expressing nutrient influx as a specific loading rate (g/m^2/yr). Residence times are not included in these guidelines, but the effect of lake volume is included because permissible rates of specific loading are greater for lakes of larger mean depth.

Table 1. SPECIFIC LOADING LEVELS FOR LAKES EXPRESSED AS TOTAL NITROGEN AND TOTAL PHOSPHORUS IN g/m^2/yr[a]

Mean depth up to:	Permissible loading, up to: N	Permissible loading, up to: P	Dangerous loading in excess of: N	Dangerous loading in excess of: P
5 m	1.0	0.07	2.0	0.13
10 m	1.5	0.10	3.0	0.20
50 m	4.0	0.25	8.0	0.50
100 m	6.0	0.40	12.0	0.80
150 m	7.5	0.50	15.0	1.00
200 m	9.0	0.60	18.0	1.20

[a] from Vollenweider (1968)

These results are based on data from 30 lakes (12 from central Europe, 10 from North America, and 8 from northern Europe) and must be considered to be provisional guidelines which require confirmation or modification by subsequent work. Nevertheless, they do provide criteria for assessing the need for nitrogen and phosphorus abatement and the potential benefits to be realized in specific situations. Shannon and Brezonik (1972) conducted a somewhat similar analysis of nutrient loadings of 55 lakes in Florida and reported permissible areal loadings of 2.0 and 0.28 $g/m^2/yr$ and critical loadings of 3.4 and 0.49 $g/m^2/yr$ for nitrogen and phosphorus respectively.

Refinement of these criteria and the determination of their regional applicability are dependent on the availability of valid nutrient loading information for numerous lakes representing a spectrum of trophic character. Ideally, these nutrient loadings would be determined by direct measurement; potentially significant sources would be identified and their contributions would be documented. However, because the costs associated with this course of action are prohibitive in most situations, it is necessary that less costly techniques be developed for use in assessing management alternatives and establishing priorities. In recent years, the technique of estimating nutrient loadings has been used in a number of situations as a guide for management decisions. The primary objective of this report is to compile nutrient flux data derived from the scientific literature and present it in a format applicable to the estimation of nutrient loadings for lakes. This report deals primarily with diffuse nutrient sources, and data are presented which may be used to estimate nutrient influx to lakes via various transport mechanisms. It is intended to provide data for predicting the quantities of nutrients which enter lakes; questions relating to the ultimate availability of these nutrients are not addressed directly.

Nutrient availability in aquatic environments encompasses several considerations. Chemical form is important. It is known that many algal species can utilize both nitrate and ammonia nitrogen, and some bluegreen algae can use molecular nitrogen as well. Orthophosphate is generally considered to be the form of phosphorus most readily utilized.

Transport processes also influence nutrient availability in aquatic systems. In addition to being in a usable chemical form, nutrients must come into physical proximity of plants at a time when they can be used. Therefore, the ultimate availability of nutrients depends not only upon their chemical form upon entry to a lake, but also upon subsequent chemical transformation and transport. Such considerations are clearly beyond the scope of this work.

The approach used in this study was to provide data in a format applicable for the estimation of loadings based on either inorganic or total forms of nitrogen and phosphorus. In many practical situations it will be advantageous to prepare an estimate for both total and inorganic loadings--the latter as an indication of the quantity of nutrients which are immediately available, and the former as a conservative estimate of the amounts which could ultimately become available.

To achieve the objectives of this report, it was necessary to convert data presented in a variety of forms into a more usable and consistent format. The units selected were: kg/ha/yr for transport from land areas, kg/ha of lake surface/yr for aerial influx, and kg/capita/yr or similar units for point source contributions. The most common difficulties encountered in accomplishing these transformations related to the identification of the chemical species reported and the analytical procedures by which the chemical determinations were made. This problem was compounded by differing sample pretreatment--some are filtered, some are not; and often these details are not given at all. An attempt was made to be rigorous but, in some instances, it was necessary to make assumptions in order to present the data in a consistent format. Also, in a few cases, data which were collected for only portions of years are included in the tables. Readers are cautioned to examine the footnotes for clarifying or restricting information.

The following terminology is used in this report:

total phosphorus: All forms of phosphorus, whether dissolved or in suspension, that are measured by an acid-oxidation procedure.

total dissolved phosphorus: The amount of phosphorus determined by an acid-oxidation procedure after sample pretreatment with 0.45 μm filtration.

dissolved inorganic phosphorus: The quantity of phosphorus as determined by a procedure for inorganic orthophosphorus after sample pretreatment with 0.45 μm filtration.

total nitrogen: All forms of nitrogen in a sample, dissolved or suspended, including NH_4-N, NO_3-N, NO_2-N, and organic-N.

organic nitrogen: Quantity of nitrogen (as NH_4-N) determined by Kjeldahl digestion.

REFERENCES

Sawyer, C. N. 1947. Fertilization of Lakes by Agricultural and Urban Drainage. New England Water Works Assoc. J. 61(2):109-127.

Shannon, E. E., and Brezonik, P. L. 1972. Relationships between Lake Trophic State and Nitrogen and Phosphorus Loading Rates. Environ. Sci. Technol. 6:719-725.

Thomas, E. A. 1953. Empirische und experimentelle Untersuchungen zur Konntnis der Minimumstoffe in 46 Seen der Schweiz. und angrenzonder Gebiete.-Schweiz. Ver. Gas & Wasserfachm. 2:1-15.

Vollenweider, R. A. 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication. Pub. No. DAS/CSI/68.27, Organisation for Economic Co-operation and Development, Directorate for Scientific Affairs, Paris, France.

NUTRIENT SOURCES AND TRANSPORT VECTORS

NUTRIENT SOURCES

In considering the flow of nutrients across the landscape it becomes clear that, in a strict sense, there are no sources or sinks, but rather, there exists a multitude of cyclic pathways along which nutrients are transported. In this context, "sources" are simply points along the nutrient flow paths which are designated for convenience. Throughout this report, an attempt has been made to incorporate the concept of potential management or control in the designation of nutrient sources and, also, to distinguish between sources and transport vectors. Toward this end, the following definitions were developed:

nutrient sources: Sites at which plant nutrients are released, or areas from which nutrients are exported, and subsequent transport is determined by uncontrolled natural mechanisms.

point source: A location at which nutrients are released in quantity and concentration compatible with practical means of nutrient removal. (example: sewage effluent)

diffuse source: An area from which nutrients are exported in a manner not compatible with practical means of nutrient removal. (example: croplands)

specific contributor: Materials or products containing nutrients which are discarded or used in a manner such that the nutrients contribute to point or diffuse sources. (example: detergents, fertilizers)

In the context of these definitions, groundwater, precipitation and dry fallout (dust fall) are treated as transport vectors, not sources of nutrients. Urban runoff is treated here as an export from a diffuse source although it is recognized that in many situations this runoff is collected in storm sewer systems and that practical means of nutrient removal may be applied in some cases.

From the standpoint of nutrient control or abatement, management action can usually be most readily applied to point sources and specific contributors. Both technological and regulatory approaches can be used. Control of nutrient transport from diffuse sources is generally aimed toward reducing the efficiency of transport mechanisms (for example, contour farming to minimize runoff from agricultural lands).

The concepts of pathway definition and mode of transport are particularly important for estimating nutrient flux from diffuse sources because nutrients may be exported simultaneously along many pathways and can be transported by several mechanisms. For example, soil particles from a given area could become airborne and reach a lake via dry fallout or precipitation. Storm runoff could transport nutrients overland to an inflowing stream, or rainwater could percolate through the soil profile to the groundwater aquifer and subsequently enter a lake directly or through the base flow of tributary streams. Waterfowl could feed in a field and deposit nutrients in a lake. These are just a few of many potentially significant modes of transport.

CONTRIBUTING AREAS

Table 2 gives a listing of transport mechanisms for nutrients, points of entry to a lake, and the land areas which contribute nutrients via the various modes of transport. It is apparent from this tabulation that, with respect to a particular lake, the land areas contributing nutrients are not identical for all modes of transport. Nutrients contained in rainfall may

Table 2. "NATURAL" MODES OF NUTRIENT TRANSPORT TO LAKES

Mode of transport	Entry to lake	Contributions from
Groundwater	land-water interface	unknown portion of groundwater drainage basin
Surface water		
a) streamflow	inlet streams	direct drainage basin
b) streamflow	inlet streams	indirect drainage basin
c) overland flow	lake perimeter	immediately adjacent lands
Precipitation	lake surface	?
Dry fallout	lake surface	?
Miscellaneous		
a) waterfowl	lake surface	-
b) N-fixation	-	-

have been transported for great distances through the air before returning to earth, and the area contributing these nutrients defies description. A similar situation exists for other transport mechanisms which involve air pathways.

Lands contributing nutrients to shallow groundwater aquifers can be defined more clearly since boundaries of groundwater basins are often approximately the same as the surface drainage basins. However, it is not necessary that all groundwater leaving the basin pass through the lake and, since the extent of communication between ground and surface waters is often poorly defined, it is extremely difficult to determine that portion of the total groundwater basin actually contributing water to a lake. Contributing lands can only be defined with reasonable certainty when surface water transport is considered.

Even if all lands within a lake's drainage basin are taken into account, it is clear that 1) it is not necessary that all nutrients exported from the land ultimately reach the lake and, conversely, 2) it is not necessary that those nutrients which are transported to a lake originate from sources within the drainage basin. The nature of the situation dictates that estimates of nutrient input from diffuse sources be based on considerations of the transport mechanism involved, and nutrient sources are taken into account only indirectly. Also, land use characteristics can only be related directly to nutrient transport to lakes via surface water flows. Lack of definition of contributing areas prohibits the application of land use data to other modes of transport.

Contributing Areas - Surface Water Transport

For purposes of estimating nutrient flux from watersheds, it is often convenient to subdivide the topographic drainage basin into two or possibly three units: the direct drainage basin, the indirect basin, and immediately adjacent lands. This latter category is of lesser importance, and would probably be used only in special situations. Small lakes with highly-developed shorelines may be one situation where this delineation would be advantageous.

The direct drainage basin is defined as that portion of a lake's drainage basin which does not drain to upstream lakes or impoundments. The indirect basin(s) include all lands draining to lakes upgradient from the lake in question. These lakes may or may not have surface water outlets. Immediately adjacent lands are a part of the direct basin and are defined as those areas from which runoff drains overland directly to a lake without entering a stream.

An illustration of these basin divisions is given in Figure 1. Two indirect basins are shown in the sketch, but only one contributes surface water to the lake below.

Indirect drainage basin

By definition, if surface waters cross the boundary between indirect and direct drainage basins, the transfer occurs only at the outlet of a lake. All water flowing from the indirect drainage basin must first pass through a lake, which is not only a point of concentration for flow, but is also a discontinuity in the nutrient pathway. It is known that, in general, lakes act as partial nutrient traps; more nutrients are received than are discharged. Therefore, a lake is a buffer which retards nutrient flow and protects downstream waters from the influence of lands above. If the lake has no outlet stream, the drainage basin contributes no nutrients via surface water to lakes below.

In view of the difficulties involved in defining the flow of nutrients through lakes, it is most convenient to treat the lake outlet as a point source which incorporates the contribution from all lands upstream. This approach requires that the volumetric rate of outflow and the corresponding nutrient concentrations be determined or estimated, but avoids the necessity of defining land use practices throughout the basin and estimating the efficiency with which the lake inhibits nutrient passage.

In most instances, it is desirable to determine mean flowrates and nutrient concentrations on a seasonal basis which corresponds to the thermal regimen of the lake. For deep lakes in temperate zones, four periods should be considered to account for: ice cover, spring overturn, summer stratification, and fall overturn. Ideally, both flow data and nutrient data would be available for the lake in question.

Many lakes have control structures at the outlet. Some have a fixed sill which acts as a broadcrested weir and, if water level elevations are recorded, the rate of outflow can be computed with reasonable accuracy. Others have release gates which are manipulated to regulate outflow, and in these situations flow records are often maintained. Streamflow records at some point in the channel downstream may also be used if they are adjusted to account for inflow received below the lake.

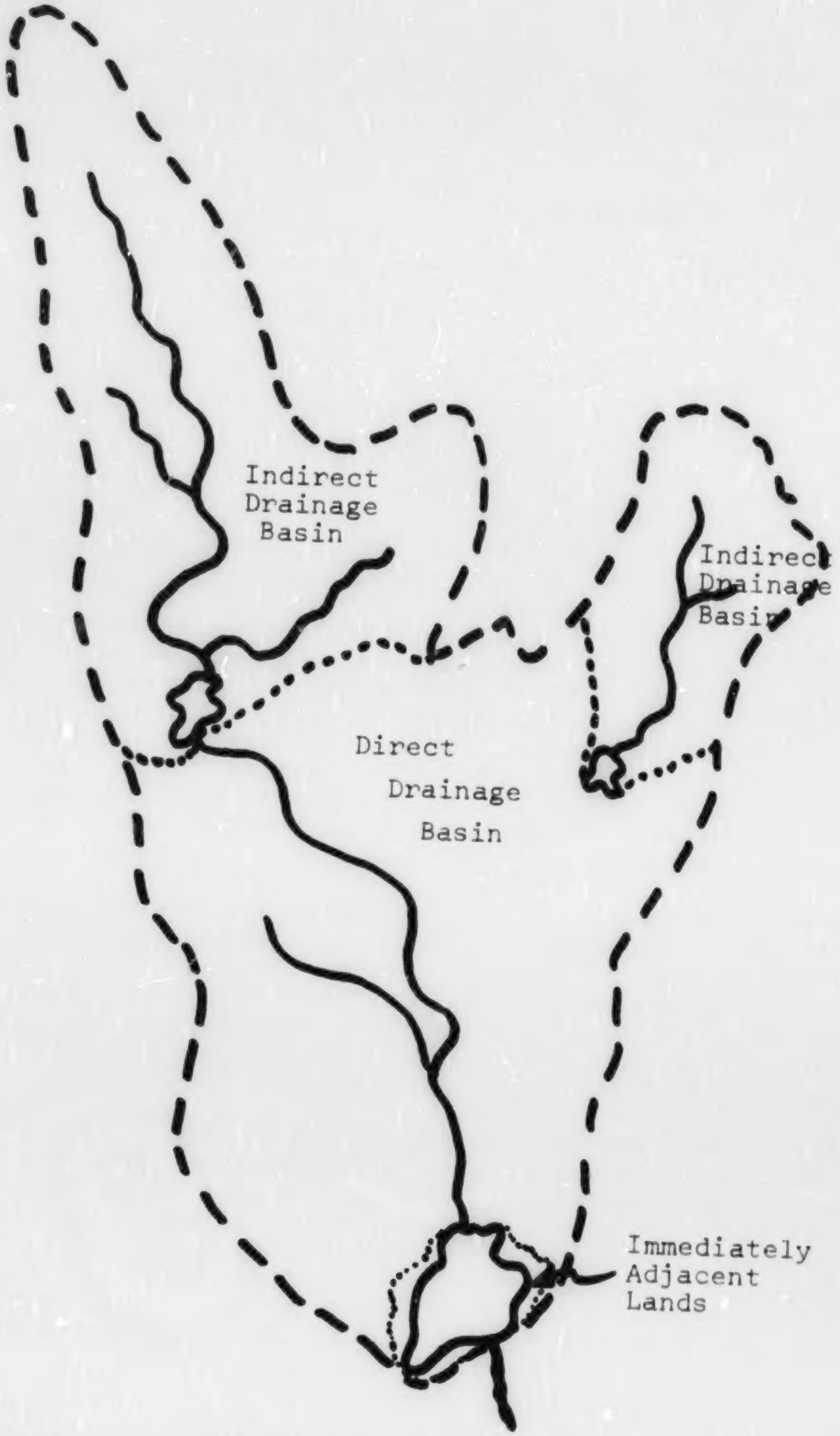
Indirect
Drainage
Basin
Indirect
Drainage
Basin
Direct
Drainage
Basin
Immediately
Adjacent
Lands

Figure 1. SUBDIVISION OF DRAINAGE BASINS

If flow records are not available, it is possible to synthesize the outflow hydrograph from rainfall-runoff relationships. By estimating that portion of total precipitation which results in runoff, and accounting for storage in snow cover, reasonable estimates of total discharge for the selected time periods can be prepared. A technique such as this does not yield accurate results for short time periods, but is adequate to describe the average total discharge that might be expected to occur during a period of several months.

In those situations where lake releases are controlled by outlet structures, it is important to establish the depth from which waters are discharged because this may have a significant effect on both the quantity and form of nutrients which are released. Dunst, Wirth and Uttormark (unpublished data) found that continuous hypolimnetic discharge increased the total amount of phosphorus and nitrogen released from a small impoundment in southwestern Wisconsin by 22% and 25% respectively as compared to nutrient output via a surface spillway. Furthermore, during periods of stratification, the majority of nitrogen and phosphorus in the hypolimnetic discharge waters was in readily available forms--NH_4-N and dissolved inorganic-P. In contrast, nutrients contained in waters released from the surface of lakes are often in forms not readily available to aquatic plants.

Immediately adjacent lands

Because of their proximity, shorelands have a greater potential for contributing nutrients to lakes than lands which lie in remote portions of the drainage basin. Therefore, in those situations where shorelands are devoted to uses which result in high rates of nutrient flux, it may be desirable to treat these lands separately for purposes of loading calculations. For example, it is reasonable to assume that particulate forms of nutrients exported from shorelands will be transported to the lake, whereas this is far less likely for distant lands. Lakes surrounded by flat, forested areas with extensive ground cover probably receive only minor contributions from immediately adjacent lands, and delineation of these areas is probably not important. In contrast, the contribution to some lakes, particularly impoundments formed in steep-sided valleys surrounded by cultivated farmlands, could be considerable, and separate consideration of these areas would be justified. This may also be the case for lakes which are surrounded by residences where lawns are maintained.

REFERENCE

Dunst, R. C., T. L. Wirth, and P. D. Uttormark. 1974. Effect of Bottom Water Discharge upon the Limnology of a Reservoir. Wisconsin Dept. of Natural Resources, Madison, Wis.

NUTRIENT EXPORT FROM AGRICULTURAL LANDS

The transport of nutrients from agricultural lands to lakes could occur along innumerable pathways and could involve many transport mechanisms. For purposes of this report, water is considered to be the primary transport vector, although it is recognized that nutrient loss by wind-blown particulate matter could be large in some instances.

Three data groupings were prepared which describe the flux of nitrogen and phosphorus from agricultural lands: 1) seepage studies, 2) runoff studies and 3) drainage area studies. The first two study types refer to the transport of nutrients across the boundaries of land areas. The latter type refers to nutrient transport by continually flowing streams. It is important to recognize that only a few of the investigations cited were conducted to quantify nutrient runoff from watersheds to lakes. The objective of most studies was to measure nutrient loss from distinct land parcels. Therefore, questions of subsequent nutrient transport must be addressed before the data can be used for estimating nutrient contributions from agricultural lands.

Seepage studies include lysimeter work and analyses of tile-drained fields. Data from these investigations may be useful in estimating the transport of nutrients from surface soils to groundwater aquifers, but the applicability of these results to the estimation of lake loadings depends greatly on the extent of groundwater-surface water exchange in the basin under consideration.

Losses of nutrients by storm runoff have been quantified in a number of studies. However, the ability to predict nutrient loadings from these data is again limited by the difficulty in defining the probability of transport from agricultural lands to lakes. This difficulty is amplified by the fact that a large portion of the nutrients lost from agricultural lands is associated with particulate matter which may settle out at intermediate points along the flow path, especially during overland flow or in intermittent stream channels.

From the standpoint of lake loadings, some of the most useful data are provided by drainage area studies because of the clearly defined pathway for nutrients contained in continually-flowing streams. However, some trade-offs are involved. Land use patterns are defined clearly for most seepage and runoff studies, but subsequent transport of nutrients to a lake is questionable. In contrast, nutrient flow paths are more clearly defined for drainage area studies, but descriptions of land use are very imprecise (i.e., "typical rural environment" or "mixed farmlands and woodlots").

FERTILIZERS

Large quantities of commercial fertilizers are applied annually to agricultural lands throughout the United States. Typical application rates range from 20-200 kg N/ha and from 10-50 kg P/ha. Because of the large amounts used, fertilizers have often been singled out as potentially important contributors to lake eutrophication. Although many studies have been conducted and much has been written, it is difficult to assess the importance of nutrient runoff from fertilized croplands because many determining factors are site-specific and, in addition, precipitation characteristics are important.

The application of fertilizers increases the amount of nutrients which could potentially be lost from agricultural lands, but offsetting factors have been shown in some instances to more than compensate for the increased potential. Proper application, which includes matching the quantity and composition of fertilizer to crop needs and soil fertility, can reduce the amount of nutrient loss from croplands by increasing nutrient utilization by plants, and by increasing crop density which reduces surface runoff and erosion. Conversely, if the addition of fertilizers creates a nutrient imbalance, or if excessive rainfall occurs shortly after application, nutrient losses can be large.

Taylor et al (1971) compared the additions of fertilizers to farmlands (near Coshocton, Ohio) to the subsequent nutrient loss via runoff, and found no relationship between the two. They identified variations in water flow as the most significant variable determining nutrient loss.

Similar results were reported by Kilmer et al (1971) from studies of two watersheds in North Carolina where fertilizer applications to bluegrass sod were evaluated. During the first two years of a three-year study, about 10 kg/ha per year more nitrogen was lost from the fertilized watershed than from the unfertilized watershed (fertilizer applied at 112 kg N/ha).

However, during the third year, fertilizer was applied to both watersheds and reduced levels of nitrogen loss were noted; in fact, the nitrogen loss from the watershed receiving fertilizer for the first time was less than for either of the two years when no fertilizer was used.

In general, the deep seepage loss of nitrogen is the major export pathway from agricultural lands. Both nitrate and ammonium are mobile in soil systems and are readily transported by seepage water. Zwerman et al (1971) reported that seepage losses of nitrogen may be as high as 225 kg/ha/yr. Runoff losses were reported to be generally small except in those instances when heavy rainfall occurred immediately after fertilizer application.

Phosphorus, unlike nitrogen, is not particularly mobile within the soil, and phosphate ions do not leach readily. Phosphorus is held tightly as a complex anion by clays, and the amount of phosphate in solution in the soil water at any one time is small. Most phosphorus is removed from soil systems by either crop uptake or soil erosion. Soil erosion can be diminished by using sound conservation practices such as increasing soil aggregation by the addition of organic residues and providing cover crops to reduce the impact of rainfall and erosion.

Data showing an increase in annual loss of nitrogen and phosphorus in tile drainage water from fertilized crops was presented by Webber and Elrick (1967) (Table 3). Drainage effluent

Table 3. ANNUAL LOSS OF N, P, AND SUSPENDED SOLIDS IN TILE DRAINAGE WATER, WOODSLEE, ONTARIO[a]

	N (kg/ha)		P (kg/ha)		Suspended solids (kg/ha)	
	No fert	Fert[b]	No fert	Fert	No fert	Fert
Bluegrass sod	0.2	0.2	0.01	0.02	15.5	29.7
Continuous corn	5.7	11.9	0.19	0.21	93.0	84.0
Corn (rotation)	4.6	11.5	0.10	0.15	30.7	38.0
Alfalfa (2nd yr)	4.9	5.7	0.07	0.18	29.5	33.5

[a] from Webber and Elrick (1967)

[b] 335 kg/ha 5-20-10 fertilizer applied for all crops each year plus 110 kg N/ha on the corn.

from a tiled area of Brookston clay at Woodslee, Ontario was analyzed over a 6-year period (1961-1966). Average annual nitrogen losses ranged from 0.2 kg/ha under bluegrass sod to 11.9 kg/ha under fertilized continuous corn. Average phosphorus loss ranged from 0.01 kg/ha/yr (unfertilized bluegrass sod) to 0.21 kg/ha/yr (fertilized continuous corn).

Timmons, Burwell and Holt (1968) analyzed the water and sediment fractions of runoff samples from experimental plots near Morris, Minnesota. (See Table 4.) The 0.009 ha plots were on loam soil at 6% slope. Crop residues were left on plots following harvest and some fertilizer was applied. Except for the plots of hay, 78-94% of the nitrogen lost in surface runoff was associated with particulate matter, and nitrogen loss increased as the density of crop cover decreased. The same general trend is shown for phosphorus loss, but a smaller portion of the total amount exported is contained in the sediment fraction. These results illustrate the importance of erosion control for minimizing nutrient loss from croplands.

Table 5 gives data presented by Eck (1957) which show some effects of slope and crop cover on the loss of nitrogen and phosphorus in surface runoff of selected test sites. In general, nutrient export increased as the slope increased (different soils types, however), and more nutrients were lost from row crops than from cover crops. The ratio of N/P in the runoff water was more dependent on soil type than crop cover.

Although this study and the one conducted by Timmons et al (1968) were not designed to evaluate the effects of fertilizer use directly, they do illustrate the importance of erosion control and crop density--factors which can be influenced significantly by fertilizer use.

Holt et al (1970) presented data showing increased nutrient concentrations in runoff from fertilized land as compared to an unfertilized control, and also the importance of incorporating fertilizers into the soil.

Fertilizer application	Total phosphorus (mg/l) in runoff
Control (no fertilizer)	0.08
Broadcast and plowed under	0.09
Broadcast and disked in	0.16
Broadcast (no soil treatment)	0.30

Table 4. NUTRIENT EXPORT IN SURFACE RUNOFF FROM EXPERIMENTAL PLOTS--SEDIMENT AND WATER FRACTIONS[a]

Crop	Total-N kg/ha/yr	%	Total-P kg/ha/yr	%
Hay:				
sediment	0.0	0	0.0	0
water	3.5	100	0.23	100
total	3.5	100	0.23	100
Oats:				
sediment	5.2	87	0.03	75
water	0.8	13	0.01	25
total	6.0	100	0.04	100
Corn (1):				
sediment	4.3	78	0.04	36
water	1.2	22	0.07	64
total	5.5	100	0.11	100
Corn (2):				
sediment	13.	94	0.11	61
water	0.8	6	0.07	39
total	13.8	100	0.18	100
Fallow:				
sediment	63	94	0.34	87
water	3.9	6	0.05	13
total	66.9	100	0.39	100

Fertilizer applied:

corn (1)	56 kg N/ha	29 kg P/ha
corn (2)	112 kg N/ha	29 kg P/ha
oats	18 kg N/ha	30 kg P/ha

[a] Based on Timmons, Burwell and Holt (1968)

Table 5. EFFECT OF CROP COVER AND SLOPE ON NUTRIENT EXPORT VIA SURFACE RUNOFF[a]

Crop	Slope %	Soil[b]	N kg/ha/yr	P(avail) kg/ha/yr	N/P
Corn	3	A	18.	0.48	37
Oats	3	A	8.1	0.21	39
Corn	8	M	21.	0.52	40
Oats	8	M	7.7	0.24	32
Wheat	8	M	0.9	0.04	22
Tobacco	8	M	49.	2.1	23
Corn	11	F	8.9	0.64	14
Oats	11	F	35.	1.8	19
Corn	20	F	42.	2.0	21
Oats	20	F	38.	1.7	22
Hay	20	F	3.3	0.26	13

[a] after Eck (1957)

[b] A - Almena silt loam
M - Miami silt loam
F - Fayette silt loam

Other studies have demonstrated that proper use of fertilizers in concert with good plowing practices reduces nutrient loss because of increased crop cover and reduced erosion (Neal, 1944; Weidner et al, 1969; Minshall et al, 1970). Positive correlations between fertilizer additions and nutrient loss were reported by Bolton et al (1970 , Broadbent and Chapman (1950), Hendrick and Welsh (1938), and Dreibelbis (1946). Because of the complexities involved and the differing results reported in the literature, no attempt is made in this report to separate data on the basis of fertilizer usage. However, the practice of spreading manure on farmlands is treated separately later in this chapter.

NUTRIENT LOSSES BY SEEPAGE

Nutrient loss from agricultural lands by seepage through the soil profile has been a topic of interest for several decades. The majority of the earlier studies were conducted to evaluate alternative agricultural practices, such as, crop rotation, fertilizer usage, and plowing techniques, and losses of nitrate nitrogen were studied almost exclusively. In more recent years, emphasis has been placed on evaluating the effects of agricultural practices on water quality, and losses of phosphorus as well as nitrogen have been reported.

Two types of studies are reported in the literature which describe the transport of nutrients by seepage through soils. These involve the use of lysimeters or the analysis of waters which flow from tile-drained croplands.

Lysimeters are constructed by surrounding a volume of earth on the sides and bottom with an impermeable material. The enclosed soil is more or less disturbed, depending on how it is placed in the enclosure. The top is exposed to the elements, and drains are connected to the bottom, so that all water percolating through the soil profile can be collected and analyzed. Runoff and erosion are generally prevented by the design of the unit. Surface areas of these units range from 0.1 to 10m^2, and it is reported that some units have been maintained actively for periods as long as 35 years.

In some parts of the country, particularly those regions in which irrigation is practiced, large tracts of land are underlain with tiles or other subsurface collection systems. Some of the irrigation water percolates through the soil profile and is removed by these drainage systems. A number of studies have been reported in which drainage waters were sampled periodically and analyzed for nitrogen and phosphorus to measure nutrient losses. In many respects, studies of this type are similar to lysimeter studies, but the surface areas covered are much larger, and not all of the seepage water is collected--some is lost to deeper aquifers.

The data from seepage studies presented in this section are grouped according to crop, but crop cover plays only a partial (and possibly minor) role in influencing nutrient loss.

Bolton, Aylesworth, and Hore (1970) measured nutrient losses in tile drainage effluent from twelve 0.1 ha plots at Woodslee, Ontario (clay soils). Seepage flows were recorded continuously, and effluent samples were filtered to remove sediment and analyzed for total nitrogen and phosphorus. The authors concluded that the nutrient loss was influenced predominantly by the amount of water that percolated through the soil.

	Nutrient loss (kg/ha/yr)			
	N		P	
Crop	No fert	Fert	No fert	Fert
Rotation:				
Corn	5.6	15.1	0.13	0.24
Oats and alfalfa	4.3	5.7	0.13	0.13
Alfalfa, 1st year	4.8	3.9	0.13	0.15
Alfalfa, 2nd year	4.7	8.6	0.08	0.22
Continuous:				
Corn	6.6	14.0	0.26	0.29
Bluegrass sod	0.3	0.7	0.01	0.12
Mean:	(4.4)	(8.1)	(0.12)	(0.19)

after Bolton, Aylesworth, and Hore (1970)

In contrast, Sylvester and Seabloom (1962) monitored irrigation return flows in the Yakima Valley in Washington and found that more nitrate and soluble-P were lost during the 6-month non-irrigation period than during the irrigation season even though 130 cm of water were applied (average rainfall was 18 cm/yr). The return flow consisted of both surface runoff and seepage through subsurface drains which continued to flow during the non-irrigation season. Samples were collected and analyzed for nitrate, total Kjeldahl nitrogen, and dissolved and total phosphorus. This project was also described by Sylvester (1961) and separate results are given for surface and subsurface drains.

	Nutrient loss (kg/ha)		
	Irrigation season	Non-irrigation season	Annual
Nitrate-N	34.	39.	73.
Dissolved-P	0.78	1.7	2.5

after Sylvester and Seabloom (1962)

	Nutrient loss (kg/ha/yr)			
	Total-N		Total-P	
	Range	Mean	Range	Mean
Surface drains	2.8-27	(16)	1.0-4.4	(2.5)
Subsurface drains	61-186	(103)	3.8-10	(7.7)

after Sylvester (1961)

Studies in which nutrient losses from croplands by tile drainage were compared to losses via surface runoff were also conducted in California and Idaho.

Johnston, Ittihadieh, Daum and Pillsbury (1965) analyzed tile drainage effluent and surface runoff from irrigated land in the San Joaquin Valley of California. Four 19- and 60-ha plots growing cotton, alfalfa and rice were studied. The soils were heavy silty clays, and tile depth averaged 190 cm. Analyses

	Nutrient loss kg/ha/yr		Fertilizer applied kg/ha/yr	
Crop	Total-N	Total-P	N	P
Cotton and rice			300	52
Tile drainage	110.	0.19		
Surface runoff	11.	0.81		
Cotton			220	36
Tile drainage	13.	0.05		
Surface runoff	6.4	0.17		
Alfalfa			none	none
Tile drainage	3.5	0.08		
Surface runoff	1.6	0.20		
Rice			94	none
Tile drainage	42.	0.60		
Surface runoff	5.2	0.11		

after Johnston, Ittihadieh, Daum and Pillsbury (1965) were made for total nitrogen and total phosphorus. No estimates were made as to the quantity of nitrogen or phosphorus lost through deep percolation.

Carter, Bondurant, and Robbins (1971) measured nitrate and dissolved phosphorus in surface runoff and subsurface (tile) drainage from an 82,000 ha tract in southern Idaho. The major crops were alfalfa, beans, grain, sugarbeets, corn, and pasture. Precipitation averaged 21 cm per year and irrigation supplied an additional 200 cm of water annually.

Nutrient inputs in kg/ha/yr:	N	P
Fertilizer	60.	30.
Irrigation water	2.3	1.0
Precipitation	negligible	negligible
Nutrient losses in kg/ha/yr:	NO_3-N	Sol-P
Surface runoff	0.35	0.17
Tile drainage	35.	0.13
Total loss	35.	0.30

after Carter, Bondurant, and Robbins (1971)

In each of these studies, seepage losses of nitrogen were large compared to losses by surface runoff. On the other hand, phosphorus losses through surface runoff tended to be larger. However, phosphorus losses through seepage were sufficiently large to be of significance from a water quality standpoint.

Erickson and Ellis (1971) measured the nutrient content in drainage waters from three experimental farms in Michigan, and compared the nutrient losses to the amounts of fertilizer used. Analyses of seepage from uncultivated, unfertilized

	Nutrients added kg/ha/yr		Nutrients lost kg/ha/yr		Lost/added percent	
	N	P	NO_3-N	Tot-P	N	P
Ferden farm	90	39	12	0.10	13	0.2
Davis farm	39	50	8	0.09	20	0.2
Muck farm	56	17	19	1.5	(34)	(8.8)

after Erickson and Ellis (1971)

land adjacent to the Muck farm led to the conclusion that the high values of nutrient loss were in part due to accretion from surrounding lands, and that only a small part of the nitrogen and phosphorus added to the Muck farm reached the drainage water.

Losses of nitrogen as a function of fertilizer usage were also studied by Broadbent and Chapman (1950). They grew vetch, clover and mustard in lysimeters at Riverside, California. The experiment covered a 15-year period and the average water application (rainfall plus irrigation) was 89 cm.

	Fertilizer N applied (kg/ha/yr)		
	0	112	224
	Nitrogen loss (kg/ha/yr)		
Crop:			
Vetch	30	79	100
Clover	39	63	91
Mustard	20	34	45
Average loss for all crops and treatments:		56	

after Broadbent and Chapman (1950)

Allison et al (1959) reported the results of experiments conducted near Columbia, South Carolina, in which crotalaria, millet, rye, cowpeas, and corn were grown in lysimeters. The lysimeters were 1.2 meters deep and were filled with sandy soil. Fertilization was reported to be "low." The average annual rainfall was 108 cm during the 12-year period covered by the study.

	Nutrient loss in kg/ha/yr					
	NO_3-N		Total-N		Total-P	
	Range	Mean	Range	Mean	Range	Mean
Various crops	2.4-40	24	3.6-46	29	0.09-0.17	0.11
Fallow or crops returned to soil			38-140	90		
No crop:						
Fertilized		40		44		0.20
No fertilizer		30		34		0.14

after Allison et al (1959)

Dreibelbis (1946) also found a correlation between nitrate loss and fertilizer usage, but Hendrick and Welsh (1938) reported no significant differences in nitrate loss between fertilized and nonfertilized plots in a ten-year study conducted in England.

A summary of the data giving nutrient losses from croplands by seepage through the soil profile is given in Table 6. Based on considerations of nutrient pathways, data from lysimeter or subsurface drainage studies are probably most applicable for estimating nutrient loadings of lakes which receive irrigation return waters. The data may also be useful for estimating the flux of nutrients from croplands to groundwater aquifers, but subsequent transport to specific lakes would be highly speculative in most instances.

SURFACE RUNOFF FROM AGRICULTURAL LANDS

A separate data grouping was prepared for nutrient losses from agricultural lands by surface runoff. In studies of this type, samples of runoff water, including suspended matter, are collected periodically from fields or experimental plots. Runoff is not continuous, but occurs only when excessive water is applied through irrigation or rainfall.

As was the case for seepage studies, most surface runoff investigations were conducted to evaluate alternative farming practices, such as plowing techniques, crop rotations and fertilizer applications, from the standpoint of minimizing soil and nutrient losses from croplands. Consequently,

Table 6. NUTRIENT EXPORT FROM CROPLANDS BY SEEPAGE THROUGH SOIL PROFILE

	N in kg/ha/yr			P in kg/ha/yr		
Crop--study	NO_3	NH_4	Total	Dissolved inorganic	Total	References
Corn--tile drainage, Lithuania	2.6					Kinderis (1970)
Corn-oats-hay rotation--lysimeter, 120 kg N/ha added, New York	43.					Bizzell (1944)
Corn-oats-hay rotation--lysimeter, New York	2.4					Bizzell & Lyon (1928)
Corn-oats-wheat-hay rotation--lysimeter, New York	5.4 with legumes 7.4 without legumes					" " "
Corn--lysimeter, Ohio	1.9					Dreibelbis (1946)
Corn--tile drainage, Ontario						
No fertilizer			6.1	0.20[a]		Bolton et al (1970)
Fertilizer added			14.	0.26[a]		" " " "
Cotton--tile drainage, 280 kg N/ha added, California	4.1[b]					Meek et al (1969)
Cotton--tile drainage, 220 kg N/ha and 36 kg P/ha added, California			13.		0.05	Johnston et al (1965)
Cotton & rice--tile drainage, 300 kg N/ha and 52 kg P/ha added, California			110.		0.19	" " " "
Rice--tile drainage, 94 kg N/ha added, California			42.		0.60	" " " "

Table 6 (continued). NUTRIENT EXPORT FROM CROPLANDS BY SEEPAGE THROUGH SOIL PROFILE

Crop--study	N in kg/ha/yr			P in kg/ha/yr		References
	NO_3	NH_4	Total	Dissolved inorganic	Total	
Oats--lysimeter, England	2.5					Hendrick & Welsh (1938)
Barley--lysimeter, England	8.					" " "
Wheat--lysimeter, Ohio	3.					Dreibelbis (1946)
Hay--lysimeter, England	9.					Hendrick & Welsh (1938)
Timothy--lysimeter, 140 kg N/ha added, New York	12.					Bizzell (1944)
Alfalfa--tile drainage, California			3.5		0.08	Johnston et al (1965)
Alfalfa--tile drainage, Ontario			4.8	0.1		Bolton et al (1970)
Alfalfa--lysimeter, Kentucky	11.					Karraker et al (1950)
Lespedeza--lysimeter, Kentucky	65.					" " " "
Lespedeza & rye--lysimeter, Kentucky	17.					" " " "
Lespedeza & bluegrass--lysimeter, Kentucky	22.					" " " "
Legumes--tile drainage, Lithuania	1.5					Kinderis (1970)
Vetch--lysimeter, California			30.			Broadbent & Chapman (1950)
Clover--lysimeter, California			39.			" " "
Mustard--lysimeter, California			20.			" " "

Table 6 (continued). NUTRIENT EXPORT FROM CROPLANDS BY SEEPAGE THROUGH SOIL PROFILE

	N in kg/ha/yr			P in kg/ha/yr		
Crop--study	NO_3	NH_4	Total	Dissolved inorganic	Total	References
Grasses--lysimeter, New York	2.8					Bizzell & Lyon (1928)
Grasses--tile drainage, Lithuania	0.3					Kinderis (1970)
Grasses & wheat--tile drainage, Lithuania	0.8					" "
Bluegrass sod--tile drainage, Ontario			0.3	0.01[a]		Bolton et al (1970)
Meadow--lysimeter, Ohio	4.3					Dreibelbis (1946)
Pasture--lysimeter, England	2.6					Hendrick & Welsh (1938)
Various crops--tile drainage, Idaho	35.			0.13		Carter et al (1971)
Various crops--tile drainage, Washington	73.		100.	2.5	7.7	Sylvester & Seabloom (1962)
Not stated--tile drainage, Illinois	18.					Harmeson et al (1971)
Not stated--tile drainage,						
Michigan, Ferden Farm			12.		0.10	Erickson & Ellis (1971)
Davis Farm			8.		0.09	" " "
Muck Farm			19.		1.5	" " "

Table 6 (continued). NUTRIENT EXPORT FROM CROPLANDS BY SEEPAGE THROUGH SOIL PROFILE

	N in kg/ha/yr			P in kg/ha/yr		
Crop--study	NO_3	NH_4	Total	Dissolved inorganic	Total	References
Fallow (no crop)--lysimeter, South Carolina	30.				0.14	Allison et al (1959)
Fallow--lysimeter, New York	76.					Bizzell & Lyon (1928)
Fallow--lysimeter, Kentucky	82.					Karraker et al (1950)

[a] Total dissolved P

[b] $NO_3 + NO_2$ for 8 mo.

particulate material was intentionally included in the samples, and particulate, along with dissolved, nutrients were measured in most instances. Study areas were often quite small and usually the areas were devoted to single crops. Fertilization and plowing were generally uniform within a study area, but large differences occurred amongst study areas.

Data from surface runoff studies are given in Tables 7 and 8. The data are grouped according to crop, but other factors, such as slope, soil characteristics, farming practices, and antecedent soil moisture, as well as duration, frequency and intensity of precipitation, may have a greater influence on the quantity of nutrients lost from croplands. Slopes (not always given) ranged from 3-20% for the studies reported, and the annual amounts of rainfall and irrigation water ranged from 75-220 cm.

Data from surface runoff studies may be useful for estimating nutrient inputs from agricultural lands immediately adjacent to lakes. However, as shown in Table 8, by far the largest amount of nitrogen and most of the phosphorus lost from croplands were associated with particulate matter. The likelihood that particulate matter will be transported sufficiently far to enter a lake must be taken into account before surface runoff data are used to estimate nutrient contributions from croplands which exist in distant portions of a watershed.

NUTRIENT TRANSPORT BY STREAMS DRAINING AGRICULTURAL LANDS

A number of studies are reported in the literature in which streams draining predominantly agricultural watershed were monitored for nutrient content. These studies typically involved the continuous measurement of streamflow and periodic sampling for nutrient determinations. In many cases, sampling frequency was related to streamflow so that additional samples were collected during periods of high flow. The amounts of nutrients transported by the streams were then calculated from a streamflow record and a time series of nutrient concentrations. Two somewhat different approaches were used to accomplish this: 1) the flow hydrographs were subdivided into segments (usually centered about the dates on which water samples were collected), and a single nutrient concentration was then assumed to be characteristic of the total water mass passing the gaging station during each time segment; 2) sample analyses were used to develop concentration-streamflow relationships, and nutrient transport was computed by applying

Table 7. NITRATE EXPORT FROM CROPLANDS BY SURFACE RUNOFF

Crop - study	kg-N/ha/yr Range	kg-N/ha/yr Mean	Reference
Corn - Columbia, Mo.		1.1	Duley & Miller (1923)
Corn - Morris, Minn.	0.07 -0.81	0.44	Timmons et al (1968)
Cotton - Guthrie, Okla.	0.35 -0.60	0.48	Daniel et al (1938)
Wheat - " "		0.36	" " " "
Wheat - Columbia, Mo.		1.5	Duley & Miller (1923)
Oats - Morris, Minn.	0.05 -0.99	0.52	Timmons et al (1968)
Hay - " "	0.11 -0.18	0.15	" " " "
Grass sod - Guthrie, Okla.	0.001-0.05	0.03	Daniel et al (1938)
Bluegrass sod - Columbia, Mo.		0.29	Duley & Miller (1923)
Fallow - " "	2.7 -6.8	4.8	" " "
Fallow - Guthrie, Okla.		0.77	Daniel et al (1938)
Virgin woods - " "		0.01	" " " "
Burned woods - " "		0.19	" " " "
Various crops - southern Idaho		0.35	Carter et al (1971)

Table 8. NUTRIENT EXPORT FROM CROPLANDS BY SURFACE RUNOFF

Crop - study	Water only kg/ha/yr		Particulate only kg/ha/yr		Not filtered kg/ha/yr		Reference
	Total N	Total P	Total N	Total P	Total N	Total P	
Corn - Geneva, New York	11.	negl					Bryant & Slater (1948)
Corn, continuous - Columbia, Mo.			45.	9.1			Duley & Miller (1923)
Corn, rotation - Columbia, Mo.			6.7	2.4			" " "
Corn, rotation - southern Wis.					8.9-42.		Eck (1957)
Corn - LaCrosse, Wis.			1.2-3.9^a	0.78-1.8^a			Hays et al (1948)
Corn - Lancaster, Wis.					4.4	1.9	Minshall et al (1970)
Corn + cover crop - Marlboro, N.J.			12.	11.			Neal (1944)
Corn - Marlboro, N.J.			19.	21.			" "
Corn, continuous - Morris, Minn.	0.4-1.2	0.06-0.08	4.1-21.	0.03-.18			Timmons et al (1968)
Corn, rotation - Morris, Minn.	1.1-1.3	0.7	1.7-6.6	0.02-0.06			" " " "
Corn, rotation - Coshocton, Ohio					99-265	3.1-10.	Weidner et al (1969)

Table 8 (continued). NUTRIENT EXPORT FROM CROPLANDS BY SURFACE RUNOFF

Crop - study	Water only kg/ha/yr Total N	Water only kg/ha/yr Total P	Particulate only kg/ha/yr Total N	Particulate only kg/ha/yr Total P	Not filtered kg/ha/yr Total N	Not filtered kg/ha/yr Total P	Reference
Cotton + rice - California					11.	0.81	Johnston et al (1965)
Cotton - California					6.4	0.17	" " " "
Rice - California					5.2	0.11	" " " "
Soybeans - Geneva, New York	0.22	negl					Bryant & Slater (1948)
Tobacco - southern Wisconsin					37.-66.		Eck (1957)
Oats, rotation - southern Wisconsin					3.6-59.		" "
Oats - LaCrosse, Wis.			3.6-58[a]	35-39[a]			Hays et al (1948)
Oats, rotation - Morris, Minn.	0.75	0.01	5.2	0.03			Timmons et al (1968)
Wheat - Columbia, Mo.			33.	12.			Duley & Miller (1923)
Wheat, rotation - southern Wisconsin					0.9		Eck (1957)
Wheat, rotation - Coshocton, Ohio					12-35.	0.4-1.3	Weidner et al (1969)

Table 8 (continued). NUTRIENT EXPORT FROM CROPLANDS BY SURFACE RUNOFF

Crop - study	Water only kg/ha/yr Total N	Water only kg/ha/yr Total P	Particulate only kg/ha/yr Total N	Particulate only kg/ha/yr Total P	Not filtered kg/ha/yr Total N	Not filtered kg/ha/yr Total P	Reference
Hay, rotation - southern Wisconsin					1.6-4.8		Eck (1957)
Hay, rotation - Morris, Minn.	0.45-6.5	0.07-0.39	0.0-0.03	0.0			Timmons et al (1968)
Alfalfa - California					1.6	0.20	Johnston et al (1965)
Clover - Geneva, New York	0.22-0.54	negl					Bryant & Slater (1948)
Bluegrass - Geneva, New York	0.10	negl					" " "
Bluegrass sod - Columbia, Mo.			0.62	0.10			Duley & Miller (1923)
Meadow - Coshocton, Ohio					negl	negl	Weidner et al (1969)
Tomatoes + cover crop - Marlboro, N.J.			12.	18.			Neal (1944)
Tomatoes - Marlboro, N.J.			20.	29.			" "
Vegetables + cover crop - Marlboro, N.J.					8.8-16.	7.6-14.	Knoblauch et al (1942)
Vegetables - Marlboro, N.J.					21.-30.	18.-30.	" " " "

Table 8 (continued). NUTRIENT EXPORT FROM CROPLANDS BY SURFACE RUNOFF

Crop - study	Water only kg/ha/yr Total N	Water only kg/ha/yr Total P	Particulate only kg/ha/yr Total N	Particulate only kg/ha/yr Total P	Not filtered kg/ha/yr Total N	Not filtered kg/ha/yr Total P	Reference
Various crops - southern Idaho		0.17					Carter et al (1971)
Various crops - Washington					2.8-27.	1.0-4.4	Sylvester (1961)
Apple orchard - Coshocton, Ohio					0.91	1.4	Weidner et al (1969)
Forest + farmland - Tennessee Valley			1.9-3.0	0.42-0.89			Fippin (1945)
Farmland - Tennessee Valley			3.8-16.	0.78-3.7			" "
Row crops - Tennessee Valley			18.-36.	4.8-8.5			" "
Fallow - Geneva, New York	1.1-12.	negl					Bryant & Slater (1948)
Fallow - Columbia, Mo.			82.-111	37.-53.			Duley & Miller (1923)
Fallow - Morris, Minn.	1.5-6.3	0.03-0.07	28.-97.	0.17-0.50			Timmons et al (1968)

[a] Data for "cropping season" only

these relationships to the stream hydrograph and integrating over appropriate time intervals.

A summary of nutrient transport from agricultural lands by streamflow is given in Table 9. Flux coefficients for these studies are less variable than for seepage or surface runoff studies.

	Total-N (kg/ha/yr)	Total-P (kg/ha/yr)
max	13.0	2.3
min	1.2	0.03
ave	5.1	0.38

Of the 24 values of total-phosphorus that were compiled, only 7 were larger than 0.4 kg-P/ha/yr, and 6 of the 7 were from the Midwest (2 from Illinois, 4 from Wisconsin). The largest value reported, 2.3 kg/ha/yr, was determined from a study in Arkansas conducted by Gearheart (1969). In this study, streamflow draining a 3,100 km^2 watershed (80% agricultural, used primarily for pasture and poultry production) tributary to Beaver Reservoir was monitored for a seven-month period from October through April. Estimates of annual values were presented by the author. Whereas the phosphorus value was larger, the flux of nitrogen, 3.6 kg-N/ha/yr, was less than the average for other data included in this group, and the ratio of Tot-N/Tot-P was only 1.5--ratios for all other studies were greater than 10.

Phosphorus transport in the Kaskaskia River watershed in Illinois was reported by Engelbrecht and Morgan (1959, 1961). Water samples were collected at approximately weekly intervals at four sites and monthly at three additional locations during the period from April-December 1956. Some municipal effluents were discharged to the river, but contributions from these sources were subtracted from the total load, and values for land drainage are presented by the authors. Results presented as phosphorus loss/unit area/day were extrapolated linearly to annual values here.

Mackenthun, Keup, and Stewart (1968) and Mackenthun (Chairman, 1966) reported studies on the results of tributaries to Lake Sebasticook, Maine. The streams studied drained sparsely populated rural areas with no significant waste discharges. The primary crops were potatoes, apples, alfalfa, beans, and

Table 9. NUTRIENT TRANSPORT FROM AGRICULTURAL WATERSHEDS BY STREAMS

Location - comment	N in kg/ha/yr NO_3	N in kg/ha/yr NH_4	N in kg/ha/yr Total	P in kg/ha/yr Dissolved inorganic	P in kg/ha/yr Total	Tot-N / Tot-P	References
Illinois, Kaskaskia River basin							
Subbasin area / % agricultural							
32 km² / 86.0	11.				0.03[a]		Engelbrecht & Morgan (1959)[d] Harmeson et al (1971)
320 " / 86.2					0.05[a]		
2,700 " / 81.7					0.85[a]		
5,100 " / 76.0					0.44[a]		
6,900 " / 68.9					0.11[a]		
13,500 " / 76.8					0.10[a]		
Connecticut, 85 km² watershed, 50% forested, "typical rural environment"			3.4		0.22	15.	Frink (1967)
Arkansas, 3072 km² watershed, 80% agricultural			3.6		2.3	1.5	Gearheart (1969)
Potomac River Basin (Catoctin Creek) 280 km², 80% farmland, 20% forest	3.8[b]		4.3		0.27	16.	Jaworski & Hetling (1970) Jaworski et al (1969)
Ontario, tributaries of Bay of Quinte, 50% agricultural, 50% forests, many lakes and bogs							
River / Area (km²)							
Trent / 13,000			2.1		0.11	19.	Johnson & Owen (1971)
Moira / 2,700			1.8		0.08	22.	
Salmon) / 1,660			2.4		0.07	34.	
Napanee)			3.0		0.14	21.	

Table 9 (continued). NUTRIENT TRANSPORT FROM AGRICULTURAL WATERSHEDS BY STREAMS

Location - comment	N in kg/ha/yr			P in kg/ha/yr		$\frac{\text{Tot-N}}{\text{Tot-P}}$	References
	NO_3	NH_4	Total	Dissolved inorganic	Total		
North Carolina, Pigeon River watershed, 350 km^2					0.17		Keup (1968)
Maine, rural areas, sparsely populated, Stetson R, 74 km^2			1.9		0.04	48.	Mackenthun et al (1968)[d]
Wisconsin, average for 36 streams, base flow only, 5.7-370 km^2			1.2		0.10	12.	Minshall et al (1969)
Ontario, Grand R watershed, 3500 km^2					0.07		Missingham (1967)[d]
Ontario, near Toronto							
River — Area (km^2)							
West Humber (dairy farms) — 130			3.2		0.21	15.	Owen & Johnson (1966)
Little Rouge (mixed farms) — 78			8.4		0.35	24.	Neil, Johnson & Owen (1967)
Altona (mixed farms) — 54			4.0		0.17	24.	
England							
Arable land			13.				Owens (1970)
Permanent pasture			8.				

Table 9 (continued). NUTRIENT TRANSPORT FROM AGRICULTURAL WATERSHEDS BY STREAMS

Location - comment	N in kg/ha/yr			P in kg/ha/yr		Tot-N	References
	NO_3	NH_4	Total	Dissolved inorganic	Total	Tot-P	
Wisconsin, tributaries to Lakes:							
Monona	← 4.9	→	6.7	0.06			Sawyer (1947)
Waubesa	← 5.5	→	7.6	0.11	0.44	17.	
Kegonsa	← 7.2	→	9.2	0.11	0.46	20.	
Prince Edward Island, 26 km^2 watershed, 28% potato fields, remainder in pasture and woodlot				0.21			Smith (1959)
Ohio, 123 ha watershed, 25% woodlots, 50% pasture, 25% cropland (data for 4 consecutive years)	1.1		1.7	0.03			Taylor et al (1971)
	2.2		3.1	0.08			
	9.1		10.6	0.07			
	1.8		4.4	0.08			
Wisconsin, Menomonee R watershed					1.6[c]		Zanoni (1970)[e]
Wisconsin, 546 ha watershed, dairy farming, 0-15% slopes	3.1[b]	1.3	8.8	0.58	0.77	11.	Zitter (1968)

[a] Ortho-P + maximum inorganic condensed-P - Authors state that total-P values may be 20-30% higher than those reported.

[b] $NO_3 + NO_2$

[c] Total dissolved - Author states that values are within a few percent of total-P.

[d] Data given as loss/day or loss for part of a year--extrapolated linearly to an annual value.

[e] Approximated from data presented.

corn, which received an average of 82 kg/ha of phosphorus as fertilizer. Precipitation was 102 cm/yr. Water samples were collected during one- to two-week periods in February, May, July-August, and October-November. Nutrient losses per day were reported by the authors for each of the four sampling periods.

Nutrient loads in kg/ha/day

	Stetson stream		Mulligan stream	
	N	P	N	P
Winter	0.0029	0.0	No flow	
Spring	0.0086	0.00015	.00084	.00003
Summer	0.0083	0.00012	No flow	
Fall	0.0015	0.00018	.0013	.00005

after Mackenthun, Keup, and Stewart (1968)

Annual values were computed here by multiplying each daily load per season by 91.25 and summing.

Phosphorus transport from a 3,500 km² agricultural watershed in Ontario (Grand River) was reported by Missingham (1967).

Month	Total-P (kg/ha/day)
Dec	0.00014
Jan	0.00025
Feb	0.00021
Ave	0.00020

An average value of 0.0002 kg/ha/day converts to 0.07 kg/ha/yr which is, most likely, an underestimate of the amount of phosphorus transported annually from the basin.

Minshall, Nichols, and Witzel (1969) carried out a two-year study to determine the amount of nutrients in base flow of southwestern Wisconsin streams. Flow rates were determined for 36 streams with drainage areas varying from 570 to 37,000 ha. Samples were collected, and flows were measured at times when no surface runoff was entering the streams.

The area studied was 90% agricultural, with 40% in contour strip-cropped farmland (corn, oats and alfalfa), 40% in pasture, and 10% woodland. Livestock enterprises were prevalent. Soils were moderately- and well-drained silt loams, and the mean annual precipitation for the area was 83 cm. An average of 9 kg/ha/yr of nitrogen was applied as manure or artificial fertilizers.

Nutrient loss in kg/ha/yr

	1966		1967	
	Tot-N	Tot-P	Tot-N	Tot-P
High	4.2	0.25	5.5	0.49
Low	0.4	0.01	0.5	0.03
Weighted ave	1.1	0.08	1.4	0.12

after Minshall, Nichols, and Witzel (1969)

Zanoni (1970) conducted a study of the Menomonee River basin in southeastern Wisconsin, and reported that an average of 1.18 kg/ha of total soluble phosphorus was contributed annually to Lake Michigan from land drainage in the watershed. The total watershed contains 350 km^2 of which 38% is agricultural, 43% is urban, and the remaining 19% is woodlots, parks and unproductive land. An analysis of runoff from sub-basins in the watershed showed that urban areas contributed 0.58 kg/ha/yr. Drainage from the remainder of the watershed, primarily rural lands, can be computed to yield a contribution of 1.6 kg/ha/yr.

MANURE HANDLING

Manure handling problems, particularly those associated with the dairy industry in the northern portions of the country, in many instances are met by spreading of manure on frozen, snow-covered fields for several months of the year. The impervious fields, coupled with rapid runoff during spring thaws, greatly increase the possibility for nutrient losses as a result of this practice.

Nutrient characteristics of manure from domestic farm animals are given in Table 10 (based on Porcella et al, 1974). A dairy cow weighs about 450 kg, so on an annual basis the manure from a single cow would contain on the order of 38 kg of nitrogen and 25 kg of phosphorus. If it is assumed that

Table 10. NUTRIENT CHARACTERISTICS OF MANURE FROM DOMESTIC ANIMALS[a]

	"Average" weight, kg/animal	Wet manure, g/kg/day	NH_4-N, g/kg/day	Total-N, g/kg/day	P_2O_5, g/kg/day	Total-N, kg/animal/yr	Phosphorus, kg-P/animal/yr
Poultry	2	62	.26	.74	.60	0.5	0.2
Ducks	2	-	-	8.0	.60-1.6	5.8	0.2-0.5
Swine	125	74	.24	.51	.42	23.	8.
Dairy cattle	450	84	-	.23	.34	38.	25.
Beef cattle	450	66	.11	.32	.18	53.	13.
Sheep	50	72	-	.60	.25	11.	2.

[a] Based on average values presented by Porcella et al (1974).

50 cows are maintained on a 100-ha farm, that for 4 months of the year the manure from these cows is spread on frozen fields, and that 10% of the nutrients are carried in runoff waters, then about 63 kg-N and 42 kg-P would be lost. Viewing this as an annual loss distributed over the entire farm, this amounts to nutrient export rates of 0.6 kg-N/ha/yr and 0.4 kg-P/ha/yr. Comparing these values with those given in Table 9 shows that manure handling could result in a very significant loss of phosphorus from agricultural lands.

A study conducted in Vermont (Midgely and Dunklee, 1945) showed that from 4.5-13 kg-N/ha was carried in runoff waters from fields which received winter application of manure at a rate of about 1800 kg/ha (10 tons/acre). Nitrogen loss was reported to depend primarily on the amount of volatilization which occurred prior to runoff, and the effect of slope was minimal because of the impervious nature of the soil. Nitrogen losses ranged from 3.3-11.5%; phosphorus losses were similar, ranging from 4.8-10%.

Minshall et al (1970) conducted studies in southwestern Wisconsin and concluded that up to 20% of the nitrogen and 13% of the phosphorus contained in manure applied in winter on frozen ground may be lost under conditions favoring maximum early spring runoff. In one instance, a 1.5 cm rain in January caused losses of nitrogen and phosphorus amounting to 17% and 6% respectively, which corresponded to about 15 kg-N/ha and 1.9 kg-P/ha. These investigators also found that summer applications of manure incorporated into the soil resulted in less nutrient runoff than plots receiving no manure.

REFERENCES

Allison, F. E., E. M. Roller, and J. E. Adams. 1959. Soil Fertility Studies in Lysimeters Containing Lakeland Sand. Tech. Bull. 1199, U.S. Dept. of Agriculture, Washington, D.C. p. 1-62.

Bizzell, J. A. 1944. Lysimeter Experiments, VI. The Effects of Cropping and Fertilization on the Losses of Nitrogen from the Soil. Mem. 256, Agr. Exp. Sta., Cornell Univ., Ithaca, N.Y. p. 1-14.

Bizzell, J. A., and T. L. Lyon. 1928. Composition of Drainage Waters from Lysimeters at Cornell University. Proc. First International Cong. Soil Sci. Com. 2:342-349.

Bolton, E. F., J. W. Aylesworth, and F. R. Hore. 1970. Nutrient Losses through Tile Lines under Three Cropping Systems and Two Fertility Levels on a Brookston Clay Soil. Can. J. Soil Sci. 50:275-279.

Broadbent, F. E., and H. D. Chapman. 1950. A Lysimeter Investigation of Gains, Losses and Balance of Salts and Plant Nutrients in an Irrigated Soil. Soil Sci. Soc. Amer. Proc. 14:261-269.

Bryant, J. C., and C. S. Slater. 1948. Runoff Water as an Agent in the Loss of Soluble Materials from Certain Soils. Iowa State Coll. J. Sci. 22:269-312.

Carter, D. L., J. A. Bondurant, and C. W. Robbins. 1971. Water Soluble NO_3-N, PO_4-P, and Total Salt Balances on a Large Irrigation Tract. Soil Sci. Soc. Amer. Proc. 35:331-335.

Daniel, H. A., H. M. Elwell, and H. J. Harper. 1938. Nitrate-Nitrogen Content of Rain and Runoff Water from Plots under Different Cropping Systems on Vermon Fine Sandy Loam. Soil Sci. Soc. Amer. Proc. 3:230-233.

Dreibelbis, F. R. 1946. Some Plant Nutrient Losses in Gravitational Water from Monolith Lysimeters at Coshocton, Ohio. Soil Sci. Soc. Amer. Proc. 11:182-188.

Duley, F. L., and M. F. Miller. 1923. Erosion and Surface Runoff under Different Soil Conditions. Res. Bull. 63, Missouri Agr. Exp. Sta. 50 p.

Eck, P. 1957. Fertility Erosion Selectiveness on Three Wisconsin Soils. Ph.D. Thesis, Univ. of Wisconsin, Madison, Wis.

Engelbrecht, R. S., and J. J. Morgan. 1961. Land Drainage as a Source of Phosphorus in Illinois Surface Waters. Tech. Rep. W61-3, Trans. 1960 Seminar on Algae and Metropolitan Wastes, Robert A. Taft San. Engr. Ctr., Cincinnati, Ohio. p. 74-79.

Engelbrecht, R. S., and J. J. Morgan. 1959. Studies on the Occurrence and Degradation of Condensed Phosphate in Surface Waters. Sewage Indus. Wastes 31:458-478.

Erickson, A. E., and B. G. Ellis. 1971. The Nutrient Content of Drainage Water from Agricultural Land. Res. Bull. 31, Agr. Exp. Sta., Michigan State Univ., East Lansing, Mich. 16 p.

Fippin, E. O. 1945. Plant Nutrient Losses in Silt and Water in the Tennessee River System. Soil Sci. 60:223-239.

Frink, C. R. 1967. Nutrient Budget: Rational Analysis of Eutrophication in a Connecticut Lake. Environ. Sci. Technol. 1(5):425-428.

Gearheart, R. A. 1969. Agricultural Contribution to the Eutrophication Process in Beaver Reservoir. Presented at Dec. 9-12, 1969 Meeting of Amer. Soc. Agr. Engrs., Chicago, Ill. 19 p.

Harmeson, R. H., F. W. Sollo, Jr., and T. E. Larson. 1971. The Nitrate Situation in Illinois. J. Amer. Water Works Assoc. 63(5):303-310.

Hays, O. E., C. E. Bay, and H. H. Hull. 1948. Increasing Production on an Eroded Loess-Derived Soil. J. Amer. Soc. Agron. 40:1061-1069.

Hendrick, J., and H. D. Welsh. 1938. Further Results from the Craibstone Drain Gauges. Trans. Royal Highland Agr. Soc., Scotland 50:184-202.

Holt, R. F., D. R. Timmons, and J. L. Latterell. 1970. Accumulation of Phosphate in Water. J. Agr. Food Chem. 18:781-784.

Jaworski, N. A., and L. J. Hetling. 1970. Relative Contributions of Nutrients to the Potomac River Basin from Various Sources. Tech. Rep. 31, Middle Atlantic Region, Fed. Water Pollut. Con. Adm. 36 p.

Jaworski, N. A., O. Villa, Jr., and L. J. Hetling. 1969. Nutrients in the Potomac River Basin. Tech. Rep. 9, Middle Atlantic Region, Fed. Water Pollut. Con. Adm. 40 p.

Johnson, M. G., and G. E. Owen. 1971. Nutrients and Nutrient Budgets in the Bay of Quinte, Lake Ontario. J. Water Pollut. Con. Fed. 43(5):836-853.

Johnston, W. R., F. Ittihadieh, R. M. Daum, and A. F. Pillsbury. 1965. Nitrogen and Phosphorus in Tile Drainage Effluent. Soil Sci. Soc. Amer. Proc. 29:287-289.

Karraker, P. E., C. E. Bortner, and E. N. Fergus. 1950. Nitrogen Balance in Lysimeters as Affected by Growing Kentucky Bluegrass and Certain Legumes Separately and Together. Bull. 557, Kentucky Agr. Exp. Sta. p. 1-16.

Keup, L. E. 1968. Phosphorus in Flowing Waters. Pergamon Press, Oxford, England. Water Res. 2:373-386.

Kilmer, V. J., J. W. Gilliam, R. T. Joyce, and J. F. Lutz. 1971. Loss of Fertilizer Nutrients from Soils to Drainage Waters. Part I. Studies of Grassed Watersheds in Western North Carolina. Rep. 55, Water Resources Res. Inst., Univ. of North Carolina, Raleigh, N.C.

Kinderis, Z. B. 1970. Leaching of Nutrients by Drainage Waters. Soviet Soil Sci. 1:99-108.

Knoblauch, H. C., L. Kolodny, and G. D. Brill. 1942. Erosion Losses of Major Plant Nutrients and Organic Matter from Collington Sandy Loam. Soil Sci. 53:369-378.

Mackenthun, K. M. (chrm.). 1966. Fertilization and Algae in Lake Sebasticook, Maine. Robert A. Taft San. Engr. Ctr., Cincinnati, Ohio. 124 p.

Mackenthun, K. M., L. E. Keup, and R. K. Stewart. 1968. Nutrients and Algae in Lake Sebasticook, Maine. J. Water Pollut. Con. Fed. 40(2):Part 2:R72-R81.

Meek, B. D., L. B. Grass, and A. J. MacKenzie. 1969. Applied Nitrogen Losses in Relation to Oxygen Status of Soils. Soil Sci. Soc. Amer. Proc. 33:575-578.

Midgely, A. R., and Dunklee, D. E. 1945. Fertility Runoff Losses from Manure Spread during the Winter. Bull. 523, Vermont Agr. Exp. Sta.

Minshall, N. E., M. S. Nichols, and S. A. Witzel. 1969. Plant Nutrients in Base Flow of Streams in Southwestern Wisconsin. Water Resources Res. 5(3):706-713.

Minshall, N. E., S. A. Witzel, and M. S. Nichols. 1970. Stream Enrichment from Farm Operations. J. San. Engr. Div., Amer. Soc. Chem. Engineers 96(SA2):513-524.

Missingham, G. A. 1967. Occurrence of Phosphates in Surface Waters and Some Related Problems. J. Amer. Water Works Assoc. 59:187-211.

Neal, O. R. 1944. Removal of Nutrients from the Soil by Crops and Erosion. J. Amer. Soc. Agron. 36:601-607.

Neil, J. H., M. G. Johnson, and G. E. Owen. 1967. Yields and Sources of Nitrogen from Several Lake Ontario Watersheds. In: Proc. Tenth Conference on Great Lakes Research, Michigan Univ., Ann Arbor, Mich. p. 375-381.

Owen, G. E., and M. G. Johnson. 1966. Significance of Some Factors Affecting Yields of Phosphorus from Several Lake Ontario Watersheds. Pub. 15, Great Lakes Res. Div., Univ. of Michigan, Ann Arbor, Mich. p. 400-410.

Owens, M. 1970. Nutrient Balances in Rivers. J. Soc. Water Treat. and Exam. 19(3):239-252.

Porcella, D. B., A. B. Bishop, J. C. Andersen, O. W. Asplund, A. B. Crawford, W. J. Grenney, D. I. Jenkins, J. J. Jurinak, W. D. Lewis, E. J. Middlebrooks, and R. M. Walkingshaw. 1974. Comprehensive Management of Phosphorus Water Pollution. Rep. EPA-600/5-74-010, U.S. Environmental Protection Agency, Washington, D.C. 411 p.

Sawyer, C. N. 1947. Fertilization of Lakes by Agricultural and Urban Drainage. New England Water Works Assoc. J. 61(2): 109-127.

Smith, M. W. 1959. Phosphorus Enrichment of Drainage Waters from Farm Lands. J. Fish. Res. Bd. Can. 16:887-895.

Sylvester, R. O. 1961. Nutrient Content of Drainage Water from Forested, Urban and Agricultural Areas. Tech. Rep. W61-3, Trans. 1960 Seminar on Algae and Metropolitan Wastes, Robert A. Taft San. Engr. Ctr., Cincinnati, Ohio. p. 80-87.

Sylvester, R. O., and R. W. Seabloom. 1962. A Study on the Character and Significance of Irrigation Return Flows in the Yakima River Basin. Univ. of Washington, Seattle, Wash. 104 p.

Taylor, A. W., W. M. Edwards, and E. C. Simpson. 1971. Nutrients in Streams Draining Woodland and Farmland near Coshocton, Ohio. Water Resources Res. 7(1):81-89.

Timmons, D. R., R. E. Burwell, and R. F. Holt. 1968. Loss of Crop Nutrients through Runoff. Minn. Sci. 24(4):16-18.

Webber, L. R., and D. E. Elrick. 1967. The Soil and Lake Eutrophication. Proc. Tenth Conference on Great Lakes Research, Michigan Univ., Ann Arbor, Mich. p. 404-409.

Weidner, R. B., A. G. Christianson, S. R. Weibel, and G. G. Robeck. 1969. Rural Runoff as a Factor in Stream Pollution. J. Water Pollut. Con. Fed. 36(7):914-924.

Zanoni, A. E. 1970. Eutrophic Evaluation of a Small Multi-Land Use Watershed. Tech. Completion Rep., Water Resources Center, Univ. of Wisconsin, Madison, Wis.

Zitter, B. A. 1968. Quantifying Amounts of Nutrients from an Agricultural Watershed. M.S. Thesis, Agr. Engineering, Univ. of Wisconsin, Madison, Wis. 215 p.

Zwerman, P. J., et al. 1971. Management of Nutrients on Agricultural Land for Improved Water Quality. Rep. 13020 DPB 08/71, U.S. Environmental Protection Agency, Washington, D.C. 151 p.

NUTRIENT EXPORT FROM URBAN AREAS

The hydrology of urban areas contributes to the rapid transport of dissolved and suspended materials from cities to nearby receiving waters and increases the potential for nutrient transport. Two factors are particularly important: 1) the large amount of impermeable areas brought about by urban development and 2) storm sewer systems. Storm sewers provide a relatively direct pathway from virtually all parts of a city to the receiving waters; short distances of overland flow are sufficient to transport nutrients from remote portions of an urban watershed. The impermeable areas prevent infiltration and increase the intensity of surface runoff. Consequently, considerable amounts of soil and other particulate matter are eroded and transported through the storm sewer system. These characteristics, particularly the intermittent high flows, make it difficult to apply conventional methods of wastewater treatment to storm water runoff and increase the need for alternate management techniques.

A number of studies are reported in the literature in which the export of materials in urban runoff have been quantified. However, many of the earlier studies were conducted in areas served by combined sanitary-storm sewer systems, and it is virtually impossible to separate the component appearing in stormwater outlets due to overloading of sanitary sewers, from that due to urban surface runoff (Weibel, 1969). Five studies, however, have been conducted recently with the objective of determining the quality of urban surface runoff. In addition, data were compiled for three locations in which streams with predominantly urban watersheds were monitored for nutrient content. A summary of these data is given in Table 11.

The most extensive study of urban runoff was conducted in Tulsa, Oklahoma (Avco Corp., 1970). Drainage from 15 test areas was sampled and analyzed for Kjeldahl nitrogen and dissolved inorganic phosphorus. The largest annual phosphorus export, 2.9 kg/ha/yr, was from a light industrial area which was still under development. Export from all other areas fell within the range of 0.5-1.2 kg P/ha/yr. Nitrogen export ranged

Table 11. EXPORT OF NUTRIENTS FROM URBAN AREAS

Study area	kg-N/ha/yr NO$_3$	kg-N/ha/yr NH$_4$	kg-N/ha/yr Total	kg-P/ha/yr Dissolved inorganic	kg-P/ha/yr Total	References
Surface runoff studies:						
Tulsa, Oklahoma			2.1[a]	0.9[b]		Avco Corp. (1970)
Durham, North Carolina, 433 ha, 37% impermeable					1.2	Bryan (1970)
Ann Arbor, Michigan, 1540 ha	(0.9)	(0.8)	(2.1)	(1.0)	(3.1)	Burm et al[c] (1968)
Madison, Wisconsin, 50 ha, residential	0.67	.50	5.0	0.64	1.1	Kluesener & Lee (1974)
Cincinnati, Ohio, 11 ha, 37% impermeable	←	2.8 →	8.8	1.1[b]		Weibel (1969)
Drainage area studies:						
Rock Creek basin (Potomac), 20,000 ha, 60% urban, 10% forest, 30% farmland	←	1.8 →	2.3	0.02		Jaworski & Hetling (1970)
Milwaukee, Wisconsin, 3160 ha, 98% urban, 50% residential				0.57[b]		Zanoni (1970)
England, urban areas			4.			Owens (1970)

[a] organic N

[b] total disssolved-P

[c] Data given are for three months, June, July, August, only.

from 0.9-4.0 kg/ha/yr and averaged 2.2 kg/ha/yr. Population densities averaged 15 persons/ha.

One of the first studies of urban runoff was conducted by Weibel et al (1964) in an 11-ha residential and light commercial area in Cincinnati, Ohio. Resident population density was 25 persons/ha. Burm et al (1968) conducted a similar study in Ann Arbor, Michigan; however, the flux of N and P was reported for only the months of June, July and August. A comparison of these data with others in Table 11 suggests that export from the Ann Arbor area is considerably higher than that reported for other cities.

Kluesener (1972) measured nutrient export from a residential watershed in Madison, Wisconsin and suggested that phosphorus leaching from leaves may be an important component of urban runoff. This is supported to some extent by the Tulsa study (Avco Corp., 1970) where phosphorus export appeared to be related to the density of tree cover.

Jaworski and Hetling (1970) studied nutrient runoff in the Potomac basin and reported results for the Rock Creek basin which is approximately 60% urban. They found that 1.8 kg/ha/yr of nitrate-N, 2.3 kg/ha/yr of total-N, and 0.02 kg/ha/yr dissolved inorganic-P were transported from the basin. These data are not directly comparable to those listed in the upper portion of Table 11, because this study was conducted by monitoring continuously flowing streams, whereas the other data are for runoff from storm sewers.

Another drainage area study was conducted by Zanoni (1970) in which nutrient transport from the Menomonee River basin in southeastern Wisconsin was measured. It was reported that the annual loss of total soluble phosphorus from a densely populated urban sub-basin (3160 ha) amounted to 0.57 kg P/ha/yr. All samples were analyzed for total soluble phosphorus but, periodically, analyses were conducted for dissolved inorganic and total phosphorus as well. Based on these results, the author reported that, on the average, dissolved inorganic phosphorus amounted to 70-80% of total soluble, and there was very little difference between total soluble and total phosphorus.

Owens (1970) calculated the nutrient loss from urban areas to several rivers in England by subtracting sewage contributions from the total load carried by the streams.

Table 12 lists the average nutrient concentration reported for urban runoff. Data for two additional cities, Seattle, Washington (Sylvester, 1961) and Washington, D.C. (DeFilippi and Shih, 1971), are also given.

FACTORS CONTRIBUTING TO THE NUTRIENT CONTENT OF URBAN RUNOFF

Several factors have been identified as being potentially significant contributors of nutrients in urban runoff; however, for the most part, studies to document their importance have not been conducted.

1. *urban erosion* - Sediment transport, often associated with the construction industry, is often thought to be a key factor. A study of land drainage in metropolitan Detroit by Thompson (1970) indicated that the erosion from areas under urban development contributed 155 metric tons of sediment per hectare per year compared with an overall average erosion rate of about 7 metric tons per hectare per year for the metropolitan area and an overall average erosion rate of 6 metric tons per hectare per year for southeast Michigan. Thus, it was concluded that road construction and urban development would account for significant amounts of sediment even though the total acreage under construction may be relatively low.

2. *lawn fertilizers* - Use of home fertilizers to maintain luxuriant lawns and gardens is a common practice in urban areas, particularly in newer residential subdivisions. Increased use of fertilizers is likely in future years. One management approach might be to encourage the use of fertilizers which contain little or no phosphorus because, in many situations, lawns require supplemental nitrogen but there is no need for additional phosphorus.

3. *animal populations* - Surprisingly large populations of cats and dogs are maintained in many urban areas. Pets could contribute relatively large amounts of nutrients to small areas.

4. *leachate from leaves* - Cowen and Lee (undated) reported on the results of leaching experiments in which phosphorus was removed from leaves by soaking them in water. They concluded that leaves could contribute significant amounts of phosphorus to urban runoff, and advocated leaf pickup and removal and advised against burning and storing leaves in gutters.

Table 12. AVERAGE NUTRIENT CONCENTRATIONS IN URBAN RUNOFF

	mg-N/1				mg-P/1		
Study area	NO_3	NH_4	Organic	Total	Dissolved inorganic	Total	References
Tulsa, Okla			0.85		0.37		Avco Corp (1970)
Durham, N.C.						0.19	Bryan (1970)
Ann Arbor, Mich	1.5	1.0	1.0	3.5	0.8[a]	5.0	Burm et al (1968)
Washington, D.C.				2.1		1.3	DeFilippi & Shih (1971)
Madison, Wis	0.60	0.45	3.5	4.5	0.57	0.98	Kluesener & Lee (1974)
Seattle, Wash	0.5		2.0	2.5	0.08	0.21	Sylvester (1961)
Cincinnati, Ohio	← 1.0 →			3.1	0.36[a]		Weibel et al (1969)

[a] Total dissolved-P

5. *gasoline additives* - It is estimated that 2.5 million pounds of phosphorus are consumed each year as additives in gasolines burned in motor vehicles in this country. Concentrations in gasoline may be as high as 12.6 mg P/l (Bartsch, 1972). However, even if it is assumed that one-half of all gasoline is consumed in urban areas, and all of the phosphorus consumed reaches surface waters, this would amount to only 0.2-2% of the estimated phosphorus contribution from urban runoff.

6. *de-icing compounds* - Some de-icing compounds used in northern cities contain phosphorus, but an analysis by Struzeski (1971) indicates that this contribution is insignificant in most situations.

REFERENCES

AVCO Economic Systems Corporation. 1970. Storm Water Pollution from Urban Land Activity. Rep. 11034 FKL 07/70, Federal Water Qual. Adm., U.S. Dept. of the Interior, Washington, D.C. 325 p.

Bartsch, A. F. 1972. Role of Phosphorus in Eutrophication. Rep. EPA-R3-72-001, Environmental Protection Agency, Washington, D.C.

Bryan, E. H. 1970. Quality of Stormwater Drainage from Urban Land Areas in North Carolina. Rep. 37, Water Resources Research Inst., Univ. of North Carolina, Chapel Hill, N.C. 44 p. plus append.

Burm, R. J., D. F. Krawczyk, and G. L. Harlow. 1968. Chemical and Physical Comparison of Combined and Separate Sewer Discharges. J. Water Pollut. Con. Fed. 40:112-126.

Cowen, W., and G. F. Lee. Undated. Leaves as a Source of Phosphorus. Water Chemistry Prog., Univ. of Wisconsin, Madison, Wis.

DeFilippi, J. A., and C. S. Shih. 1971. Characteristics of Separated Storm and Combined Sewer Flows. J. Water Pollut. Con. Fed. 43(10):2033-2058.

Jaworski, N. A., and L. J. Hetling. 1970. Relative Contributions of Nutrients to the Potomac River Basin from Various Sources. Tech. Rep. 31, Middle Atlantic Region, Federal Water Pollut. Con. Adm. 36 p.

Kluesener, J. W. 1972. Nutrient Transport and Transformation in Lake Wingra, Wisconsin. Ph.D. Thesis, Water Chemistry Dept., Univ. of Wisconsin, Madison, Wis.

Kluesener, J. W., and G. F. Lee. 1974. Nutrient Loading from a Separate Storm Sewer in Madison, Wisconsin. J. Water Pollut. Con. Fed. 46:920-936.

Owens, M. 1970. Nutrient Balances in Rivers. J. Soc. Water Treat. and Exam. 19(3):239-252.

Struzeski, E. 1971. Environmental Impact of Deicing. Rep. WPCRS 11040 6KK 06/71, Environmental Protection Agency, Washington, D.C.

Sylvester, R. O. 1961. Nutrient Content of Drainage Water from Forested, Urban and Agricultural Areas. Tech. Rep. W61-3, Trans. 1960 Seminar on Algae and Metropolitan Wastes, Robert A. Taft San. Engr. Ctr., Cincinnati, Ohio. p. 80-87.

Thompson, J. R. 1970. Soil Erosion in the Detroit Metropolitan Area. J. Soil and Water Conservation 25(1):8-10.

Weibel, S. R. 1969. Urban Drainage as a Factor in Eutrophication. In: Eutrophication: Causes, Consequences, Correctives. National Academy of Science, Washington, D.C. p. 383-403.

Weibel, S. R., R. J. Anderson, and R. L. Woodward. 1964. Urban Land Runoff as a Factor in Stream Pollution. J. Water Pollut. Con. Fed. 36:914-924.

Zanoni, A. E. 1970. Eutrophic Evaluation of a Small Multi-Land Use Watershed. Tech. Completion Rep. OWRR A-014-Wis., Water Resources Center, Univ. of Wisconsin, Madison, Wis.

NUTRIENT EXPORT FROM FORESTS

Forested lands are known to have relatively high absorptive capacities with minimal amounts of surface runoff and accompanying soil erosion. Consequently, most studies of nutrient export from forested lands are conducted by monitoring streamflows or measuring vertical nutrient movement through the soil profile in forested areas. The only surface runoff study identified was conducted by Daniel, Elwell and Harper (1938). They analyzed surface runoff from plots of virgin woods in Oklahoma and found that nitrogen runoff as nitrate-N amounted to 0.01 kg/ha/yr.

Cole and Gessel (1965) placed tension lysimeters beneath the floor (2.5 cm depth) and the rooting zone (90 cm depth) of four 0.04-ha Douglas fir forest areas near Seattle, Washington. The soil was composed of 50 to 80% gravel. Two of the plots received added nitrogen at the rate of 224 kg/ha. Leachates were collected and analyzed monthly.

	Nutrient loss (kg/ha/yr)			
	Total N		Total P	
Treatment	Floor	Rooting zone	Floor	Rooting zone
Untreated	3.9	0.54	0.84	0.03
Clear-cut	11	0.97	2.3	0.11
Urea fertilizer	173	0.69	5.5	0.08
Ammonium fertilizer	200	1.1	4.5	0.17

after Cole and Gessel (1965)

Several studies have been conducted in which streams flowing from forested watersheds were monitored for nitrogen and phosphorus. Cooper (1969) presented data showing the quantities of nitrogen and phosphorus removed from forested areas in northern Minnesota. The data were determined from the weighted average of weekly samples collected from August to November. The forests were predominantly aspen-birch and lay in an area of poor drainage.

Nutrient Export in g/ha/day (4 months)

Watershed area (ha)	NH_4-N	NO_3-N	Organic N	Total P
2,150	0.43	7.3	5.9	0.30
2,850	0.50	6.0	5.7	0.50
958	0.31	0.7	2.6	0.23
13,000	0.43	3.2	5.5	0.37
Mean	0.42	4.3	4.9	0.35

after Cooper (1969)

Sylvester (1961) measured the nutrient content in streams emerging from three forested areas of the Yakima River basin in Washington. The watersheds contained large reservoirs, roads and some logging but no significant human habitation. The drainage areas were 47,000, 62,000, and 32,000 ha for the Yakima, Tieton, and Cedar River basins respectively.

Nutrient Export (kg/ha/yr)

	NO_3	TKN	Tot-N	Sol-P	Tot-P
Yakima	2.37	0.95	3.32	0.08	0.83
Tieton	0.95	0.51	1.46	0.05	0.86
Cedar	1.06	-	-	0.07	0.36
Mean	1.46	0.73	2.39	0.07	0.68

after Sylvester (1961)

Viro (1953) studied the nutrient loads carried by the five largest river systems in Finland, representing, in general, forest areas with granite bedrock. The total drainage area was 34 million ha, and precipitation within the drainage area varied from 45-69 cm. River water samples were taken monthly and analyzed for Kjeldahl nitrogen and total phosphorus.

River	Area (ha)	Nutrient loads (kg/ha/yr) TKN	P
Vuoksi	6.1 M	2.2	0.29
Kymijoki	4.9 M	1.6	0.26
Kokemäenjoki	8.4 M	1.8	0.29
Oulujoki	4.7 M	2.1	0.32
Kemijoki	9.5 M	1.7	0.18
Mean		(1.9)	(0.26)

after Viro (1953)

Bormann et al (1968) studied the effects of clear-cutting and herbicide treatment on a small forested watershed in New Hampshire. Nutrient losses for the treated (15.6 ha) and undisturbed (13.2 ha) areas were determined by weekly sampling and flow rate measurements of streams draining the areas. Analysis was made for ammonia and nitrate nitrogen. Annual precipitation was 125 cm. They noted little difference in the annual flux of ammonia nitrogen from the two areas, but transport of nitrate was much greater from the clear-cut area.

	Nutrient loads (kg/ha/yr) Undisturbed	Clear-cut
NH_4-N	0.5-0.6 (0.55)	0.4-1.2 (0.8)
NO_3-N	1.0-1.5 (1.3)	1.3-58. (30.)

after Bormann et al (1968)

A summary of data describing the transport of nutrients from forested areas as determined by drainage area studies is given in Table 13.

Export of total nitrogen averaged 2.9 kg N/ha/yr and ranged from 1.3 to 5.1 kg N/ha/yr. Total phosphorus flux ranged from 0.01 to 0.86 kg P/ha/yr with an average value of 0.27 kg P/ha/yr.

Table 13. NUTRIENT EXPORT FROM FORESTED WATERSHED VIA STREAMFLOW

	N in kg/ha/yr			P in kg/ha/yr		
Study area	NO_3	NH_4	Total	Dissolved inorganic	Total	References
Forested watershed, New Hampshire	1.3	0.6			0.02	Bormann et al (1968)
Woodlands, marsh, open fields, Ohio					0.67	Cooke et al (1973)
Four aspen + birch watersheds in northern Minnesota	2.7	0.16	5.1		0.11	Cooper[a] (1969)
	2.2	0.18	4.5		0.18	
	0.3	0.11	1.3		0.08	
	1.2	0.16	3.4		0.14	
88% forested watershed in the Potomac River basin	← 1.3 →		1.6		0.01	Jaworski & Hetling (1970)
Three forested areas in Washington	2.4		3.3	0.08	0.83	Sylvester (1961)
	1.0		1.5	0.05	0.86	
	1.1		-	0.07	0.36	
Woodlands in Ohio, one watershed, data for three years	0.8		1.4	0.04[b]		Taylor et al (1971)
	1.6		3.2	0.07[b]		
	0.7		2.8	0.03[b]		
Five large forested river basins in Finland			2.2[c]		0.29	Viro (1953)
			1.6[c]		0.26	
			1.8[c]		0.29	
			2.1[c]		0.32	
			1.7[c]		0.18	
Forested watershed in Sweden				0.02	0.06	Brink & Gustafson (1970)

[a] Data given for 4 months, extrapolated to 12 months.

[b] Total soluble P

[c] Total Kjeldahl N

REFERENCES

Bormann, F. H., G. E. Likens, D. W. Fisher, and R. S. Pierce. 1968. Nutrient Loss Accelerated by Clear-Cutting of a Forest Ecosystem. Science 159:882-884.

Brink, N., and A. Gustafson. 1970. Lantbrukshogskolan. No. 1, Institutionenen for Markvetenskap-Vattenvard, Uppsala, Sweden.

Cole, D. W., and Gessel, S. P. 1965. Movement of Elements through a Forest Soil as Influenced by Tree Removal and Fertilizer Additions. In: Youngberg, C. T. (ed.). Forest-Soil Relationships in North America. Oregon State Univ. Press, Corvallis, Ore. p. 95-104.

Cooke, G. D., T. N. Bhargava, M. R. McComas, M. C. Wilson, and R. T. Heath. 1973. Some Aspects of Phosphorus Dynamics of the Twin Lakes Watershed. In: Modeling the Eutrophication Process. Middlebrooks, E. J. (ed.). Pub. PRWG136-1, Utah Water Research Lab., Utah State Univ., Logan, Utah. p. 57-72.

Cooper, C. F. 1969. Nutrient Output from Managed Forests. In: Eutrophication: Causes, Consequences, Correctives. National Academy of Sciences, Washington, D.C. p. 446-463.

Daniel, H. A., H. M. Elwell, and H. J. Harper. 1938. Nitrate-Nitrogen Content of Rain and Runoff Water from Plots under Different Cropping Systems on Vermon Fine Sandy Loam. Soil Sci. Soc. Amer. Proc. 3:230-233.

Jaworski, N. A., and L. J. Hetling. 1970. Relative Contributions of Nutrients to the Potomac River Basin from Various Sources. Tech. Rep. 31, Middle Atlantic Region, Federal Water Pollut. Con. Adm. 36 p.

Sylvester, R. O. 1961. Nutrient Content of Drainage Water from Forested, Urban and Agricultural Areas. Tech. Rep. W61-3, Trans. 1960 Seminar on Algae and Metropolitan Wastes, Robert A. Taft San. Engr. Ctr., Cincinnati, Ohio. p. 80-87.

Taylor, A. W., W. M. Edwards, and E. C. Simpson. 1971. Nutrients in Streams Draining Woodland and Farmland near Coshocton, Ohio. Water Resources Res. 7(1):81-89.

Viro, P. J. 1953. Loss of Nutrients and the Natural Nutrient Balance of the Soil in Finland. Comm. Inst. Forest, Fenn. 42(1):1-51.

NUTRIENT LOSSES FROM MARSHES AND WETLANDS

Nutrient dynamics of marshes and other wetland areas is one of the more poorly-defined aspects of nutrient transport from watersheds; the role of wetlands as nutrient sources or sinks for down-gradient water bodies has not been established satisfactorily. Several factors enhance the potential of marshes to act as nutrient sinks. Flow velocities through marsh systems are generally low so, if a marsh receives runoff water, settling removes a large portion of the suspended particulate materials; high levels of photosynthesis, characteristic of wetlands, incorporate nutrients into plant tissue; and nitrogen removal also occurs through denitrification reactions. On the other hand, the periodic occurrence of anaerobic conditions increases the possibility for discharge of ammonia and soluble inorganic phosphorus, particularly in wetlands subject to pulses of high discharge from runoff.

The development of nutrient budgets for wetlands has been hampered by the complex hydrology of marsh areas. Groundwater seepage often accounts for the majority of water input, evaporation accounts for much of the output, and the rates of water exchange by these mechanisms has proven to be very difficult to measure.

Bentley (1969) studied four marshes in Wisconsin and estimated that on a long-term basis, they were neither nutrient sources nor sinks, but that the marshes tended to accumulate nutrients during the growing season and released them during spring runoff. However, even during periods of active photosynthesis, the marshes were not a barrier to nutrient transport; concentrations of dissolved inorganic phosphorus in discharge waters typically exceeded 0.01 mg/l. Bentley also reported that nitrate was largely removed from input waters through denitrification and plant uptake. Nitrogen in the discharge waters was in the form of ammonia or organic nitrogen, the majority being in the organic form.

Based on laboratory leaching studies, Amundson (1970) concluded that the practice of draining marshes negated most beneficial effects and agravated the effects detrimental to water quality. He estimated that phosphorus runoff from drained marsh lands may be as large as 5 kg/ha/yr--an amount equal to 10-20 times the normal contribution from agricultural lands.

Water quality characteristics of marshes (managed for northern pike spawning) adjacent to Houghton Lake, Michigan were studied by Novy and Pecor (1973). Typical management operations were to pump lake water into the marshes in early spring and drain them about two months later. This operation was repeated in the fall. Nutrient budget computations showed that the marshes received about 0.04 kg/ha more inorganic nitrogen than was discharged and, conversely, there was a net release of 0.04 kg/ha of phosphorus to the lake. Operations during the study year were atypical, and it was estimated that, under normal conditions, there would be no net phosphorus flux to the lake and the loss of inorganic nitrogen in the marsh would be somewhat larger than 0.4 kg/ha.

Based on these studies, it is estimated that the runoff coefficients for both phosphorus and nitrogen are approximately zero for wetlands; however, the range of conditions studied is too restrictive to establish the general validity of these findings.

REFERENCES

Amundson, R. W. 1970. Nutrient Availability of a Marsh Soil. M.S. Thesis, Water Chemistry Dept., Univ. of Wisconsin, Madison, Wis. 56 p.

Bentley, E. M. 1969. The Effect of Marshes on Water Quality. Ph.D. Thesis, Water Chemistry Dept., Univ. of Wisconsin, Madison, Wis. 197 p.

Novy, J. R., and C. H. Pecor. 1973. Impact of Northern Pike Spawning Marsh Operation on Water Quality. Tech. Bull. 73-2, Michigan Water Resources Com. and the Dept. of Natural Resources, Lansing, Mich. 40 p.

NUTRIENT INFLUX FROM GROUNDWATER

Nutrient contributions from direct groundwater influx are one of the most poorly defined components of lake nutrient budgets and, based on the fragmentary information available, these contributions can be very significant. The mobility of inorganic nitrogen in soil-water systems, along with the relatively high concentrations of nitrogen found in many groundwaters, has led to the general consensus that direct seepage through lake beds could account for a large portion of the total nitrogen loading for some lakes (Vollenweider, 1968; Lee, 1970; Keeney, 1972). Lee et al (1969) estimated that 36% of the total nitrogen influx to Lake Mendota resulted from direct groundwater seepage.

Phosphorus influx via groundwater seepage is generally thought to be quite small. Lee et al (1969) estimated that only about 2% of the phosphorus entering Lake Mendota was carried by seepage. Cooke et al (1973) measured nutrient budgets for East Twin and West Twin Lakes (Ohio) and reported data showing that groundwater influx accounted for 3.2 and 7.5% of the phosphorus entering these lakes respectively over an 18-month period.

Somewhat larger relative phosphorus contributions from groundwater have been reported for two small lakes in Wisconsin. Based on field studies, Hennings (1974) estimated that 24% of the phosphorus (and 72% of water) enter Pickerel Lake by seepage. Possin (1973) reported similar groundwater contributions of 25% phosphorus and 21% water for Mirror Lake. This latter study also indicated that the absolute input of total phosphorus was also quite significant and amounted to about 0.12 gm-P/ha/yr. A summary of these data is given in Table 14.

In very general terms, groundwater contributions are functions of 1) the nutrient concentrations in the surrounding aquifers, 2) the extent of groundwater exchange between lake and aquifer, and 3) biochemical modification of nutrient forms during seepage through the permeable material surrounding the lake, including the bottom sediments. Of these, nutrient concentra-

Table 14. NUTRIENT CONTRIBUTIONS TO LAKES VIA GROUNDWATER

Lake name	% inflow from groundwater	% total N input from groundwater	% total P input from groundwater	N loading from groundwater, gm/m^2/yr	P loading from groundwater, gm/m^2/yr	Reference
East Twin	11%		3.2%		.023	Cooke et al, 1973
West Twin	25%		7.5%		.027	Cooke et al, 1973
Pickerel	72%	44%	24%	1.4	.033	Hennings, 1974
Mirror	21%	34%	25%	1.74	.12	Possin, 1973

tions in the surrounding aquifer can be determined most readily. The latter two considerations present considerably more difficulty.

Water budget measurements have been used to calculate groundwater exchange with lakes (Allred et al, 1971; Salo and Cooperman, 1972), but the accuracy of this technique is often limited by difficulties associated with the determination of evaporation losses--a second "unknown" in the water budget equation. More importantly, the budget approach gives only net exchange, and this information may be insufficient from the standpoint of nutrient loadings. For example, Born, Smith and Stephenson (1974) compiled data for 64 lakes in glaciated, temperate regions of North America and reported that 40% of these were "flow-through" lakes with respect to groundwater, i.e. groundwater inflow and outflow occurred simultaneously within the lakes' basins. Water budget studies would underestimate the magnitude of groundwater influx in lakes of this type.

Stephenson (1971) modified results presented by Walesh (1966) and compiled a list of techniques that could be used for investigating groundwater-surface water exchange, and discussed the applicability of these techniques to lakes. (See Table 15.) He emphasized that field investigations are necessary to establish the degree of water exchange between lakes and surrounding aquifers. A thorough discussion of the hydrologic regime of glacial-province lakes, including a classification scheme for various types of groundwater exchange with lakes, is given by Born, Smith and Stephenson (1974).

The relative contributions of groundwater to the water budget of 22 lakes are given in Table 16. These data illustrate the wide range of conditions which occur and emphasize the need for on-site investigations if one is to account for nutrient influx--and outflow--via subsurface water movement.

Even when quantities of groundwater exchange are known, the role of lake sediments in altering nutrient constituents of seepage waters must be taken into account when estimating loadings. Keeney et al (1971) measured denitrification rates in sediments using ^{15}N-labeled nitrate and, based on in-situ experiments in Lake Mendota, they estimated that two-thirds of the nitrate entering the lake by seepage would be "lost" from the lake system because of denitrification in the lake sediments. (It is possible that groundwater seepage through lake sediments has a greater impact on lakes by providing a mechanism for enhancing nutrient recycling, than it does by

Table 15. PARTIAL LIST OF METHODS FOR INVESTIGATING THE GROUNDWATER-SURFACE WATER INTERCHANGE

	Factors required in application of method									
Method of study	Geologic framework	Hydrologic data	Flow system description	Permeability	Water-surface map	Steady-flow	Flow-field dimensions	Adaptable to anisotropy	Adaptable to nonhomogeneity	Easily adaptable to lake studies
Analytical (mathematical)										
Hydrologic balance		X				assumed	3			X
Flow net	useful	useful	X	X	X	X	2	possible		X
Numerical (digital)	X		X	X	limited	X	3	X		X
Well equations	X		X	X	X	X	3			limited (seepage)
Electrical										
Resistance network analog	X		X	X		X	3	X	X	X
Conductive solid	X		X	X	limited	X	2	X		limited
Conductive liquid	X		X	X	limited	X	3	X	X (with 2-D flow)	X
Physical										
Sand tank	X		X	X	limited		3	X	X	X (grossly)
Hele-Shaw	X		X	X	limited		2	X	X	

from Stephenson (1971)

Table 16. GROUNDWATER CONTRIBUTIONS TO THE WATER BUDGET OF LAKES

Lake name	Location	Area (ha)	Max depth (m)	gw inflow / tot inflow	gw outflow / tot outflow	Reference
Oyster Pond	near Woods Hole, Mass	25	6	83%	0(?)	Emery (1969)
Lake Sallie	Becker Co, Minn	486	17	14%	0	Mann & McBride (1972)
Pitcher Lake	near St. Paul, Minn	3	3	-	(net)15%	Allred et al (1971)
Booster Club Pond	Anoka Co, Minn	3	2	-	(net)18%	" " " (1971)
Mud Lake	Sibley Co, Minn	13	2	-	(net)10%	" " " (1971)
Ria Lake	near Newport, Minn	4	2	-	(net)40%	" " " (1971)
Lake Poinsett	Hamlin Co, Minn	3965	5	10.30%	2%	Barari (1971)
Krause Pond	Langlade Co, Wis	0.4	4	∿100%	0	Carline (1973)
Sunshine Springs	Langlade Co, Wis	0.4	4	∿100%	0	" (1973)
Snake Lake	Vilas Co, Wis	6	5	50%	>0	Born et al (1973)
Pickerel Lake	Portage Co, Wis	16	5	72%	?	Hennings (1974)
Mirror Lake	Waupaca Co, Wis	4	14	21%	16%	Possin (1973)
Shadow Lake	Waupaca Co, Wis	16	14	41%	2%	" (1973)

Table 16 con't. GROUNDWATER CONTRIBUTIONS TO THE WATER BUDGET OF LAKES

Lake name	Location	Area (ha)	Max depth (m)	$\frac{\text{gw inflow}}{\text{tot inflow}}$	$\frac{\text{gw outflow}}{\text{tot outflow}}$	Reference
Jyme Lake	Oneida Co, Wis	0.4	3	0	~30%	Smith et al (1972)
East Twin	Portage Co, Ohio	27	12	11%	0	Cooke et al (1973)
West Twin	Portage Co, Ohio	34	12	25%	0	" " " (1973)
Little St. Germain	Vilas Co, Wis	384	5	24%	0	Hackbarth (1968)
Muskellunge	Vilas Co, Wis	111	6	44%	0	" (1968)
Lake Quinsigamond	Worchester Co, Mass	312	26	(net)20-60%		Salo & Cooperman (1972)
Deep Lake	Grand Coulee, Wash	49		98%	0	Friedman & Redfield (1971)
Lake Lenore	Grand Coulee, Wash	445		33%	9%	Friedman & Redfield (1971)
Soap Lake	Grand Coulee, Wash	336		84%	8%	Friedman & Redfield (1971)

[a] Modified from Born, Smith and Stephenson (1974)

adding nutrients from outside sources. However, only this latter aspect is considered here.)

Considering the present state of knowledge, there appear to be no general guidelines for the estimation of nutrient influx via groundwater. More research is needed in this area, particularly for flow-through lakes where a net loss of nutrients could occur even though there may be a net addition of water to a lake. Direct management applications, such as the location of septic tanks in areas where groundwater movement is away from lakes, add further support for a better definition of the groundwater regime of lake systems.

REFERENCES

Allred, E. R., P. W. Manson, G. M. Schwartz, P. Golany, and J. W. Reinke. 1971. Continuation of Studies on the Hydrology of Ponds and Small Lakes. Tech. Bull. 274, Univ. of Minnesota, Agr. Exp. Sta., St. Paul, Minn.

Barari, A. 1971. Hydrology of Lake Poinsett. Rept. Inv. 102, South Dakota Geological Survey, Vermillion, S.D.

Born, S. M., S. A. Smith, and D. A. Stephenson. 1974. The Hydrogeologic Regime of Glacial-Province Lakes, with Management and Planning Applications. Inland Lake Renewal and Management Demonstration Project Report, Dept. of Natural Resources and the Univ. of Wisconsin, Madison, Wis.

Born, S. M., T. L. Wirth, J. O. Peterson, J. P. Wall, and D. A. Stephenson. 1973. Dilutional Pumping at Snake Lake, Wisconsin--A Potential Renewal Technique for Small Eutrophic Lakes. Tech. Bull. 66, Dept. of Natural Resources, Madison, Wis.

Carline, R. F. 1973. Spring Pond Research--A Progress Report. Dept. of Natural Resources, Madison, Wis.

Cooke, G. D., T. N. Bhargava, M. R. McComas, M. C. Wilson, and R. T. Heath. 1973. Some Aspects of Phosphorus Dynamics of the Twin Lakes Watershed. In: Middlebrooks, E. J., D. H. Balkenborg, and T. E. Maloney (eds.). Modeling the Eutrophication Process. PRWG136-1, Proc. Workshop, Utah State Univ., Utah Water Research Lab., Logan, Utah. p. 57-72.

Emery, K. O. 1969. A Coastal Pond Studied by Oceanographic Methods. American Elsevier, New York.

Friedman, I., and A. C. Redfield. 1971. A Model of the Hydrology of the Lakes of the Lower Grand Coulee, Washington. Water Resources Res. 7(4):874-898.

Hackbarth, D. A. 1968. Hydrogeology of the Little St. Germain Lake Basin, Vilas County, Wis. M.S. Thesis, Univ. of Wisconsin, Madison, Wis.

Hennings, R. G. 1974. A Hydrologic Investigation of the Pickerel Lake Basin, Portage County, Wisconsin. M.S. Thesis, Univ. of Wisconsin, Madison, Wis.

Keeney, D. R. 1972. The Fate of Nitrogen in Aquatic Ecosystems. Literature Review No. 3, Water Resources Center, Univ. of Wisconsin, Madison, Wis.

Keeney, D. R., R. L. Chen, and D. A. Graetz. 1971. Importance of Denitrification and Nitrate Reduction in Sediments to the Nitrogen Budget of Lakes. Nature 233:66-67.

Lee, G. F. 1970. Eutrophication. Occasional Paper No. 2, Water Resources Center, Univ. of Wisconsin, Madison, Wis.

Lee, G. F. (chrm.). 1969. Report on the Nutrient Sources of Lake Mendota. Lake Mendota Problems Committee, Madison, Wis.

Mann, W. B., IV, and M. S. McBride. 1972. The Hydrologic Balance of Lake Sallie, Becker County, Minnesota. Prof. Paper 800-D, U.S. Geologic Survey. p. D189-D191.

Possin, B. N. 1973. Hydrogeology of Mirror and Shadow Lakes in Waupaca Co., Wisconsin. M.S. Thesis, Univ. of Wisconsin, Madison, Wis.

Salo, J. E., and A. N. Cooperman. 1972. Lake Quinsigamond Water Quality Study--1971. Pub. 6306, Massachusetts Water Resources Com., Div. of Water Pollut. Con.

Smith, S. A., J. O. Peterson, S. A. Nichols, and S. M. Born. 1972. Lake Deepening by Sediment Consolidation--Jyme Lake. Univ. of Wisconsin and Wisconsin Dept. of Natural Resources, Inland Lake Demonstration Project, Madison, Wis.

Stephenson, D. A. 1971. Groundwater Flow System Analysis in Lake Environments, with Management and Planning Implications. Water Resources Bull. 7(5):1038-1047.

Vollenweider, R. A. 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication. Pub. DAS/CSI/68.27, Organisation for Economic Cooperation and Development, Directorate for Scientific Affairs, Paris, France.

Walesh, S. G. 1966. Ground Water-Surface Water Interchange--A Summary of Methodology. Unpub. Independent Study, Geol. 999, Univ. of Wisconsin, Madison, Wis.

NUTRIENT CONTRIBUTIONS FROM SEPTIC TANKS

Traditionally, the criteria for assessing the adequacy of septic tank/soil absorption systems have been related to health considerations. Design specifications or conditions for approval (permit requirements) of on-site domestic waste treatment systems generally relate to the presence of soil types with infiltration capacities sufficient to prevent surface discharge of effluent and to prevent contamination of drinking water supplies. Nutrient migration from soil absorption fields has been of concern only recently.

A compilation and review of data describing the composition of household wastewater are given by Ligman et al (1974). Considering bath, toilet, kitchen and laundry, household wastewaters contain about 6.5 kg-N and 1.5 kg-P per capita ("average adult") per year. These values were based on fulltime occupancy, and 50% of the phosphorus originated from the laundry. Therefore, lesser loadings would be expected for septic tanks serving seasonal lakeshore properties. Ellis and Childs (1973) reported the phosphorus load in household wastewater to be about 0.5 kg/capita/year without laundry and 1.6 kg/capita/year with laundry.

Nutrient attenuation in the soil absorption field is dependent upon the loading rate, permeability and absorption capacity of the soil, depth of overburden above the water table, and groundwater movement in the saturated zone. Bouma et al (1972) showed that the formation of crusts in the seepage field greatly altered performance by reducing infiltration rates 20- to 100-fold and permitting unsaturated conditions to persist in seepage beds. Ellis and Childs (1973) documented the down-gradient migration of nitrate and phosphorus for distances up to 100 and 43 meters from drain fields, respectively.

Field measurements of the amount of phosphorus adsorbed to soils in septic tank seepage beds around Houghton Lake, Michigan are also reported by Ellis and Childs (1973). Maximum observed values for four soil types--expressed as mg-P/kg of soil--are given below.

Soil type	Observed maximum (mg-P/kg soil)
Rifle peat	50
Newton loamy sand	120
Rubicon sand	135
Nester loam	150-300

The influence of phosphorus retention capacity on the migration of phosphorus from septic tank systems is illustrated by the following data presented by Ellis and Childs (1973). Each site received a "high" phosphorus loading, and the data columns refer to values obtained within 3 m of the drainfields, or at distances greater than 13 m from the drainfields.

Depth (m)	Newton loamy sand P-retention, mg/kg		Rifle peat P-retention, mg/kg	
	(3m)	(13m)	(3m)	(13m)
0-0.3	151	84	19	4
0.3-0.7	117	79	18	23
0.7-1.0	121	17	7	8
1.0-1.3	102	18	14	5

after Ellis and Childs (1973)

The Newton loamy sand adsorbed much of the phosphorus input and still retained some adsorption capacity at 13 m from the drainfield. The Rifle peat showed much lower phosphorus retention, indicating that phosphorus was migrating through the soil to the lake; this was documented by groundwater sampling.

A conservative (high) estimate of nutrient loadings to lakes from septic tank seepage can be computed by applying the factors 1.5 kg-P/capita/yr and 6.5 kg-N/capita/yr to each lakeshore dwelling served by septic tank systems. These values can be reduced, when appropriate, to account for seasonal occupancy, lack of laundry facilities, areas where groundwater movement is away from the lake, and phosphorus retention capacity of soils. Phosphorus retention efficiencies range from nearly 100% in loamy soils to almost zero for older systems in peat or light sand.

REFERENCES

Bouma, J., W. A. Ziebell, W. G. Walker, P. G. Olcott, E. McCoy, and F. D. Hole. 1972. Soil Absorption of Septic Tank Effluent, a Field Study of Some Major Soils in Wisconsin. Information Circular No. 20, Univ. of Wisconsin-Extension, Madison, Wis. 235 p.

Ellis, B., and K. E. Childs. 1973. Nutrient Movement from Septic Tanks and Lawn Fertilization. Tech. Bull. No. 73-5, Dept. of Natural Resources, Lansing, Mich. 69 p.

Ligman, K., N. Hutzler, and W. C. Boyle. 1974. Household Wastewater Characterization. J. Environ. Engr. Div., ASCE. 100(EE1):201-213.

ATMOSPHERIC CONTRIBUTIONS OF NITROGEN AND PHOSPHORUS

Data were compiled which describe the quantity of nitrogen and phosphorus contributed annually via bulk precipitation at locations throughout the continental United States. Bulk precipitation is defined to include rainfall, snowfall, and dry fallout (dust fall). All data were converted to a rate of nutrient input expressed in kg/ha/yr. Data presented originally as nutrient concentrations in rainfall were converted by multiplying the concentrations by appropriate conversion factors and the 30-year average rainfall for that location as compiled and published in the National Atlas by the U.S. Geological Survey for the years 1935-1965. A large amount of nitrogen data was found. However, because of the scarcity of phosphorus data specific to the United States, data for other locations were included as well. Lake loading values can be computed by multiplying the tabulated coefficients by the surface area of a lake.

Two related approaches were utilized in this phase of the study: 1) a compilation of data for specific locations and 2) a cartographic approach based on nitrogen concentrations in precipitation.

FACTORS AFFECTING NUTRIENT CONTENT OF BULK PRECIPITATION

The majority of authors found that a simple parts-per-million measurement of the constituents of rain was a less accurate prediction of eventual total contribution of nutrients than such factors as geographic location, agricultural land use, and season. Two prominent authors, Yaalon (1964) and Junge (1958), have suggested a relationship between acidity and temperature of the soil and total final contribution. Unfortunately, each study seems to suggest correlations and hypotheses distinct to that area of study.

In an early study in Ottawa, Shutt (1925) reported that "there was no direct proportionality between the volume of rainfall or snowfall and the quantity of nitrogen furnished annually per acre." Since then, numerous confirming studies have been reported. Matheson (1951) concluded there "were no simple correlations with atmospheric conditions" in his study in Hamilton, Ontario. Gambell and Fisher (1966) found similar results in Virginia and concluded "no single present theory seems adequate to explain the characteristics shown by the network NO_3 data." Allen et al (1968) also confirmed this lack of correlation from studies in England where he found "periods of very high rainfall are associated with greater quantities of the elements but that the converse is also true. . . . .I can see no consistent pattern in months' fluctuations across sites in either occurrences or magnitudes." The only study that proposed a correlation ($r = 0.9$[illegible]) was conducted by Chojnachi and M. Kac Kacas (1966) in the Pulway Region of the Soviet Union. Unfortunately, only the abstract has been translated into English.

This lack of correlation is the result of many factors, and dry fallout appears to be of critical importance. Whitehead and Feth (1964) estimated that between four to ten times the nutrient content of rain falls as bulk precipitation. Eriksson (1952), after exhaustive testing in Scandinavia, concluded that fallout may contribute three times as much nitrogen as precipitation. Matheson (1951) determined that dry fallout comprises 40% of the total nitrogen contribution from the atmosphere for Canada, while Junge (1958) estimated that 70% of the atmospheric nitrogen contribution in arid climates comes from dry fallout. Kluesener (1972) found that for Madison, Wisconsin the nitrogen contribution from dry fallout is double that of precipitation, while for phosphorus it is up to three times that of rainfall.

Distribution of precipitation between rain and snow has also been cited as an important factor. Shutt (1925) and Barica and Armstrong (1971) in their Canadian studies found that snow contributions were considerable and that concentrations in snow (water equivalent) may be significantly higher than in rain. In their findings snow contributed from one-fourth to over one-half of the total, although snow comprised a far smaller proportion of total precipitation.

Gore (1968) analyzed rainfall over a six-year period at Moor House in northern England, and presented data which illustrate annual variations at one site.

Year	Rain cm	Inorganic-N kg/ha/yr	Total-P kg/ha/yr
1959-60	179	-	0.3
1960-61	191	-	0.9
1961-62	203	10.7	0.3
1962-63	186	12.5	1.8
1963-64	179	14.5	0.6
1964-65	176	18.6	1.1
Ave	186	14.0	0.8

after Gore (1968)

Another study conducted in England by Allen et al (1968) illustrates geographical variations in atmospheric contributions of nitrogen and phosphorus.

Study site	Rain cm/yr	Nutrient contributions kg/ha/yr	
		Total-N	Total-P
40 km from sea (8 km from chemical plant)	95	19.0	0.8
Forested lake district 15 km from sea	174	-	0.3
	162	9.5	0.4
	172	8.7	0.3
Open moorland 19 km from North Sea	95	8.9	0.2
Coniferous forest 8 km from North Seas	116	13.0	0.8

after Allen et al (1968)

The contribution of phosphorus via bulk precipitation has been studied less intensively than nitrogen because, for both agriculture and lake management, other sources of phosphorus are likely to be more important. Schraufnagel et al (1967) estimated that only 1.2% of the phosphorus found in Wisconsin waters was contributed by precipitation, and Sridharan (1972) estimated that the contribution of phosphorus via bulk precipitation in

Green Bay was only .5% of the total. Gore (1968) noted that the scarcity of data resulted from the relative unimportance of atmospheric sources and aerial pathways of nutrients and that limited research has generated "insufficient data" so far, to draw conclusions as to the possible sources of rainwater phosphorus. From a study of two sites in England he speculated that possible extraneous sources were household dust and smoke.

In addition to scarcity of data, sampling problems and temporal and regional variations of phosphorus concentration in precipitation complicate data interpretation. Gore (1968) reported that phosphorus utilization by microorganisms can result in a 30% underestimation of the phosphorus content unless a preservative such as iodine is added to sampling vessels. He also reported that bird defecation causes serious sampling problems.

Several researchers reported considerable seasonal variations in the phosphorus content of rain. Reimbold and Daiber (1967) sampled rainfall in Delaware and found phosphorus concentrations in summer to be more than 20 times those found in late winter and spring.They attributed these variations to "unusual phosphorus cycles found in the bay areas and marshes along the eastern United States." They also stress the influence of agricultural activity during spring planting and of dust from unpaved roads. Tamm (1951) also identified these contributory factors. Allen et al (1968) found peak concentration to occur in December, March and June in England, and also noted that "the phosphorus quantity showed no consistent close relationship with the quantity of rain, except occasionally for the extremely high and low rainfalls." Kluesener (1972) conducted studies in Wisconsin and found that highest concentrations occurred in May which he attributed to seeds, birds, and pollen. In England, Carlisle et al (1966) also identified these sources as contributing to increases in phosphorus concentrations. Particularly high concentrations, about 5 times those reported in most Western countries, were reported by Vijayalakshmi and Pandalai (1962) in India during the monsoon season.

Although considerable differences were noted between findings of the various investigators, there are some areas in which consensus has been reached. It is generally agreed that storms and prevailing winds off the ocean are low in phosphorus content and that the major source of phosphorus in rainfall is from dust generated over the land. Urbanization and industrialization are cited by Voigt (1960) and others as major contributors. Soil erosion, industrial ash, and smoke are also commonly listed.

Unfortunately, data interpretation is complicated by significant differences which exist between the various studies reported. In some, only the contribution from rainfall was measured; gaging instruments were closed during periods of no rain. Others used open gages that measured both dustfall and rainfall, and some were constructed to handle snowfall. In addition, techniques for chemical analyses have changed considerably during the time span of the reported studies, which greatly complicates data interpretation; only recent papers express concern for nitrogen loss through denitrification, or shifts in chemical species during sample storage prior to analysis.

Data describing atmospheric contributions of nitrogen and phosphorus are summarized in Tables 17 and 18 respectively. These tables contain more than 125 determinations of the annual atmospheric contribution of nitrogen in its various forms at some 60 locations in the United States and Canada and over 33 values of phosphorus loadings throughout the World. These represent the measurements of more than 50 scientists over a period of 50 years and can be taken as independent data points for checking the reasonableness of estimations presented in this paper and of any on-site experimental results of nitrogen and phosphorus contribution from the atmosphere. Care, however, must be taken to incorporate the information provided in the footnotes for these tables because only then are the numbers comparable.

CARTOGRAPHIC PRESENTATION OF NITROGEN CONTRIBUTIONS FROM PRECIPITATION

The most comprehensive research regarding the nitrogen content of rainfall was reported by Junge (1958). In this paper, he reported concentrations of nitrate and ammonia at over 60 gaging stations across the United States. Data were grouped into seasonal concentrations of four three-month periods over the year from July 1955 to July 1956. The study was designed so that results would be comparable with those found by Eriksson (1952) in his investigations of precipitation in Scandinavia. As a result, gages were located at U.S. weather stations away from large urban areas and industrial sites and were designed to record only precipitation and not bulk fallout. They were also equipped with a heating device to melt ice and snow.

A common problem in gaging experiments of this type is to keep organic matter out of the collection receptors (Gore, 1968). The primary source for such organic matter is bird droppings,

Table 17. ATMOSPHERIC CONTRIBUTIONS OF NITROGEN[a]

Study	Rainfall cm	N contribution in kg/ha/yr			Reference
		NO_3-N	NH_4-N	Total N	
Northeastern U.S.					
Windsor, Conn				4.5	Jacobson et al (1948)
Washington, D.C.	105	5.1	0.6		Junge & Werby (1958)
New Brunswick, N.J.		5.6	5.6		Prince et al (1941)
New Jersey	115		3.3	9.2	Malo & Purvis (1964)
Albany, N.Y.	91	8.4	1.5		Junge & Werby (1958)
Geneva, N.Y.	100		8.6	10.1	Collison et al (1933)
Geneva, N.Y.		6.7			Bizzell (1944)
Ithaca, N.Y.	100	1.1			Wilson (1921)
Ithaca, N.Y.	100	1.4	4.5		Leland (1952)
Ithaca, N.Y.	75	8.0	4.1		Buckman & Brady (1961)
Southeastern U.S.					
Tallahassee, Fla	140	2.3	0.8		Junge & Werby (1958)
Cape Hatteras, N.C.	137	3.2	1.2		Junge & Werby (1958)
Cape Hatteras, N.C. (120 mi at sea)	121	0.5	1.0		Gambell & Fisher (1964)
Greenville, N.C.	119	8.0	1.3		Junge & Werby (1958)
N. Carolina - high		2.7[b]			Gambell & Fisher (1966)
N. Carolina - ave	121	1.7[b]			Gambell & Fisher (1966)
N. Carolina - low		0.5[b]	0.5[b]		Gambell & Fisher (1966)
N. Carolina-Virginia		1.4			Gambell & Fisher (1964)
Roanoke, Va	127	8.9	2.4		Junge & Werby (1958)

Table 17 continued. ATMOSPHERIC CONTRIBUTIONS OF NITROGEN[a]

Study	Rainfall cm	N contribution in kg/ha/yr			Reference
		NO_3-N	NH_4-N	Total N	
Midwest U.S.					
Urbana, Ill	94	2.3	0.7		Junge & Werby (1958)
Urbana, Ill	94			1.7	Larson & Hettick (1956)
Indianapolis, Ind	100	4.6	2.1		Junge & Werby (1958)
Kentucky	112	8.0			Freeman (1924)
Kentucky		0.8			Johnson (1925)
Duluth, Minn	80	1.8	1.9-4.7		Putnam & Olson (1960)
Columbia, Mo	102	8.7	3.5		Junge & Werby (1958)
Columbia, Mo	102			22.4[b]	Woodruff (1949)
Cincinnati, Ohio	110	0.2-15.4[c]			Weibel et al (1964)
Coshocton, Ohio	78	17.5[c]			Taylor et al (1971)
Coshocton, Ohio	89	20.0[c]			Taylor et al (1971)
Coshocton, Ohio	89	20.0[c]			Taylor et al (1971)
Coshocton, Ohio	93	20.9[c]			Taylor et al (1971)
Hancock, Wis	45			4.1	Shah (1962)
LaCrosse, Wis	43			7.2	Shah (1962)
LaCrosse, Wis	116			9.6	Shah (1962)
Madison, Wis	44			4.5	Shah (1962)
Madison, Wis	102			19.6	Shah (1962)
Madison, Wis	107			16.7	Shah (1962)
Madison, Wis	90	3.1	2.8	7.7	Kluesener (1972)
Madison, Wis	-	6.5[b]	6.8[b]	23.0[b]	Kluesener (1972)

Table 17 continued. ATMOSPHERIC CONTRIBUTIONS OF NITROGEN[a]

Study	Rainfall cm	N contribution in kg/ha/yr			Reference
		NO_3-N	NH_4-N	Total N	
Midwest U.S. con't					
Marshfield, Wis	69			4.2	Shah (1962)
Marshfield, Wis	86			13.1	Shah (1962)
Milwaukee, Wis	52			4.4	Shah (1962)
Sturgeon Bay, Wis	100			18.5	Shah (1962)
West-Central Wis - rural	90	2.8-3.5[b]	2.9-12.2[b]	13.2-30.1[b]	Hoeft (1971)
West-Central Wis - urban	90	3.7[b]	3.6[b]	13.5[b]	Hoeft (1971)
West/Southwest U.S.					
Fresno, Calif	24	1.6	4.1		Junge & Werby (1958)
Riverside, Calif				9.0-14.6	Broadbent & Chapman (1950)
San Diego, Calif	28	1.9	2.4		Junge & Werby (1958)
Grand Junction, Colo	23	1.3	0.6		Junge & Werby (1958)
Glasgow, Mont	38	3.3	2.2		Junge & Werby (1958)
Ely, Nev	38	0.7	1.0		Junge & Werby (1958)
Guthrie, Okla	75	1.1			Daniel et al (1938)
Goodwell, Okla	46	0.6			Finnel & Houghton (1931)
Oklahoma	50	0.8			Finnel & Houghton (1931)
Amarillo, Tex	53	2.0	1.2		Junge & Werby (1958)
Brownsville, Tex	64	2.5	1.4		Junge & Werby (1958)
Tacoma, Wash	203	4.6	0.8		Junge & Werby (1958)

Table 17 continued. ATMOSPHERIC CONTRIBUTIONS OF NITROGEN[a]

Study	Rainfall cm	N contribution in kg/ha/yr NO_3-N	NH_4-N	Total N	Reference
Canada					
Hamilton, Ont		1.8		3.2	Matheson (1951)
Hamilton, Ont		3.7^b		6.5^b	Matheson (1951)
Ottawa, Ont	60	2.4	5.0		Buckman & Brady (1961)
Ottawa, Ont	62	2.0	4.4		Shutt & Hedley (1925)
Ottawa, Ont	(snow)	0.5	0.8		Shutt & Hedley (1955)
Ottawa, Ont		2.4^b	4.4^b	7.8^b	Shutt (1925)
Northwest Ontario	snow			$(4.3)^d$	Barica & Armstrong (1971)
Northwest Ontario	snow			$(5.8^b)^d$	Armstrong & Shindler(1971)

Footnotes:
a - Unless noted, all values are for rainfall only.
b - bulk precipitation
c - NO_3 + NH_4
d - data for 4 months only

Table 18. ATMOSPHERIC CONTRIBUTIONS OF PHOSPHORUS^a

Study	Rainfall cm	P contribution kg/ha/yr Inorganic	Total	Reference
North America				
New Haven, Conn			0.10	Voigt (1960)
Delaware	100		0.56	Reimbold & Daiber (1967)
Cincinnati, Ohio			0.80	Weibel et al (1966)
Kent, Ohio			0.14	Cooke et al (1973)
Northwest Ontario	snow		(0.40^b)^c	Armstrong & Shindler (1971)
Northwest Ontario	snow		(0.27^b)^c	Barica & Armstrong (1971)
Green Bay, Wis			0.08	Sridharan (1972)
Madison, Wis		0.18	0.23	Kluesener (1972)
Madison, Wis		0.33^b	1.02^b	Kluesener (1972)
Other				
Australia, Melbourne			0.30	Attwill (1966)
Czechoslovakia			0.07-0.16	Chalupa (1960)
England			0.20	Allen et al (1968)
England			0.43	Carlisle et al (1966)
England - high			1.09	Gore (1968)
England - ave			0.85	" "
England - low			0.12	" "
France			0.40	Farrugia (1960)
Gambia			0.17	Thornton (1965)

Table 18 continued. ATMOSPHERIC CONTRIBUTIONS OF PHOSPHORUS[a]

Study	Rainfall cm	P contribution kg/ha/yr Inorganic	P contribution kg/ha/yr Total	Reference
Other con't				
Germany			0.13	Ottermann & Krzysch (1965)
Ghana			3.3	Nye (1961)
India, Kerala			4.75	Vijayalakshmi & Pandalai (1962)
Italy			1.6-2.0	Imporato (1964)
Nigeria			0.4-2.6	Jones (1960)
Russia, Voronezh			0.3	Sviridova (1960)
Scandinavia			0.15-0.50	Tamm (1951)
Scandinavia	100		1.0	Tamm (1953)
South Africa, Natal			8.0	Ingham (1943)

a - Unless noted, all values are for rainfall only.
b - bulk precipitation
c - data for four winter months only

which has forced many investigators to construct elaborate gaging vessels that must be continually cleaned and checked for the presence of bird defecation by testing for abnormally high phosphorus concentrations. This care is important because not only will the presence of such matter give very high ammonia readings, but it also increases the chances for denitrification to occur. Junge (1958) avoided problems of bird waste by having the collectors covered except during the time of actual precipitation, which accounts for the absence of dry fallout information also. Denitrification was kept to a minimum by using plastic containers which permitted exchange of oxygen, and samples were stored no longer than 30 days prior to analysis.

Consideration of factors which could potentially influence Junge's results leads to the conclusion that, if the data are not truly representative, they are biased toward underestimating the nitrogen content of rainfall.

One possible source of error results from the manual operation of the rain gages. Individuals housed at the gage sites were to keep the gages covered until the rains began, at which point the sampling vessels were to be uncovered. However, as Gambell and Fisher (1964) and others have pointed out, the concentration of nutrients in rain water, especially ammonia, is highest at the beginning of storms and declines very rapidly thereafter. Gambell and Fisher found very rapid washout in the first minutes of a storm when ammonia concentration dropped from 8 to 1 ppm. This phenomenon was especially pronounced in storms of high turbulence and intensity. Angstrom and Hoberg (1952) described this decline in concentration as an exponential reduction with time. Therefore, it would appear that even if the gages were left covered for only a short time at the beginning of storms, considerable ammonia could have been lost.

Site location could also significantly influence results. Hoeft (1971) showed that the proximity to agricultural animal concentrations is a dominant factor in nutrient contributions. Also, organic nitrogen is relatively high in these situations. Junge located his collection sites at the outskirts of urban areas and in small towns to avoid industrial concentrations. These sites were probably located near sparse animal concentrations. Therefore, in states with high animal concentrations in the rural areas, Junge's data probably underestimate the nutrient contribution from the atmosphere.

Junge's results were presented in map form with isobars separating the country into regions of uniform concentration of nitrogen in precipitation. Each map represented a three-month period, and nitrate and ammonia were mapped separately. These concentrations were converted to loadings (kg/ha/yr) in this study by using 30-year averages for monthly precipitation at the sampling sites. It should be noted that in some instances exact sampling locations are not given in the 1958 paper of Junge and Werby or in three previous papers, Junge (1956), (1958a), (1958b), which describe the methodology for the project.

Loadings for nitrate and ammonia were computed separately and then combined to cover a one-year period. These combined data points were transferred to a map (Figure 2) and isobars of equal contributions in terms of kg/ha/yr were drawn under the assumption of linear transformation between data points. The gradient between isolines is 0.5 kg/ha/yr. This increment was selected to show the relative pattern of loadings; the approach used is not sufficiently accurate to justify further interpolation. These patterns are suggestive of general input distribution but may be subject to considerable local variation.

Based on Figure 2, the region bordering the southern Great Lakes receives the largest input of nitrogen from atmospheric sources, and loading values on the order of 3.0-3.5 kg N/ha/yr were calculated. However, as discussed above, it is likely that the values shown in this figure are underestimates of the actual loading. Dry fallout was not included in the calculations, and it has been estimated that this factor could account for 40-90% of the nitrogen input (Hoeft, 1971; Kluesener, 1972). A comparison of the loading rates shown in Figure 2 with the data in Table 17 shows considerable discrepancies at some locations and, in general, it appears that the loading rates shown in Figure 2 are low by a factor of 3 or 4. If this is the case, then the Great Lakes region of the United States may receive an atmospheric contribution of nitrogen at a rate of about 10 kg/ha/yr. This corresponds to the permissible loading rate of 1.0 $g/m^2/yr$ for lakes with mean depths less than 5 meters (Vollenweider, 1968). It would appear, therefore, that for this region of the country, it may be extremely difficult to limit the influx of nitrogen to levels considered permissible or satisfactory from the standpoint of controlling eutrophication in shallow lakes because atmospheric contributions alone could be large.

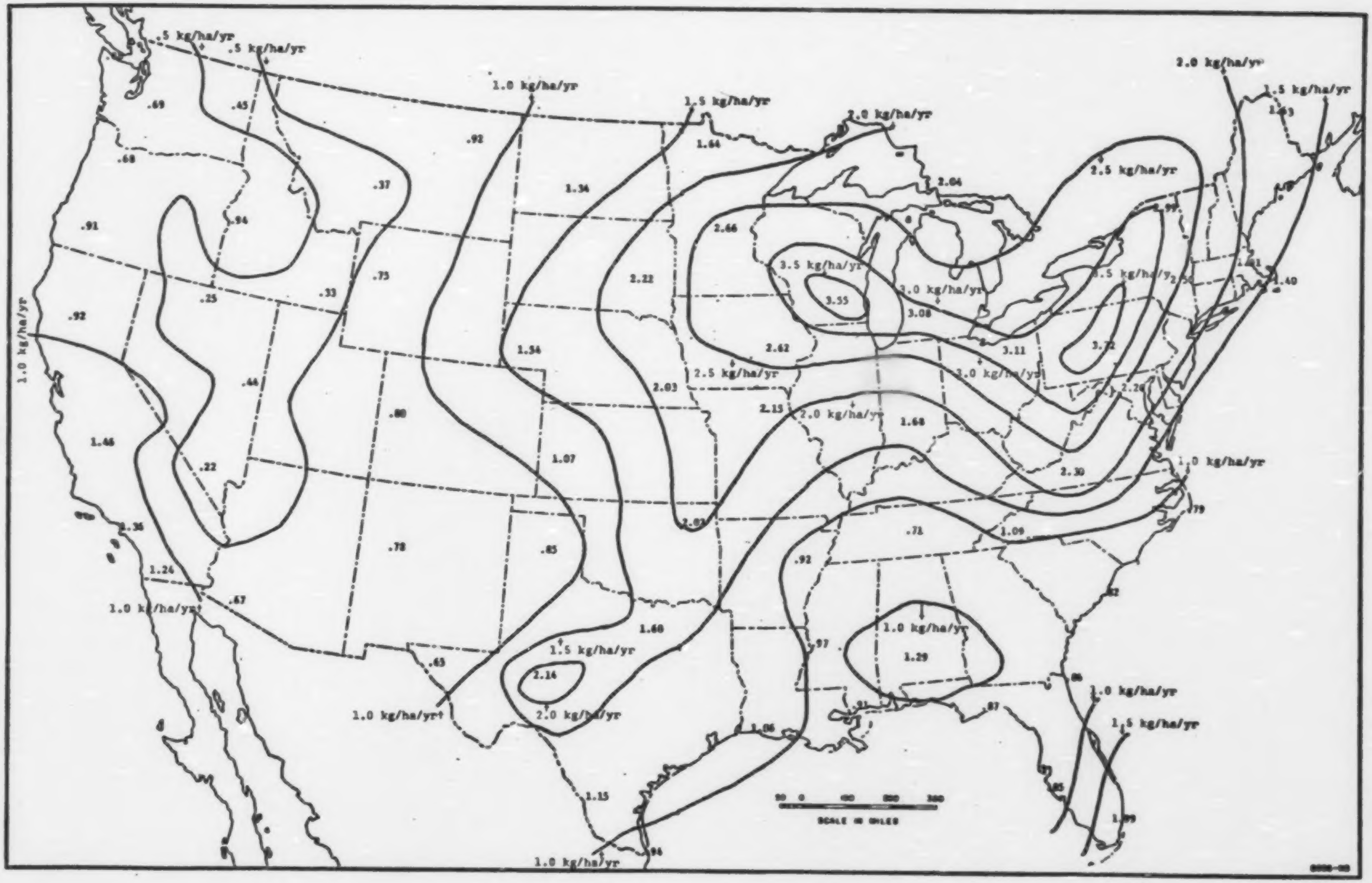
.5 kg/ha/yr
.5 kg/ha/yr
1.0 kg/ha/yr
1.5 kg/ha/yr
2.0 kg/ha/yr
2.0 kg/ha/yr
1.5 kg/ha/yr
2.5 kg/ha/yr
3.5 kg/ha/yr
3.0 kg/ha/yr
3.5 kg/ha/yr
2.5 kg/ha/yr
3.0 kg/ha/yr
2.0 kg/ha/yr
1.0 kg/ha/yr
1.0 kg/ha/yr
1.5 kg/ha/yr
2.0 kg/ha/yr
1.0 kg/ha/yr
1.0 kg/ha/yr
1.0 kg/ha/yr
1.0 kg/ha/yr
1.5 kg/ha/yr
.69
.45
.68
.92
.37
.91
.94
1.34
1.64
2.04
.25
.33
.75
2.22
2.66
.92
.44
1.54
2.03
2.62
3.55
3.08
3.11
3.72
1.46
.80
2.13
1.68
2.30
.22
1.07
2.07
1.09
.79
.36
.78
.85
.71
1.24
.67
.63
2.14
1.60
.92
.97
1.29
.87
1.06
1.15
.94
1.63
1.40
2.26
SCALE IN MILES

Fig. 2. NITROGEN CONTRIBUTIONS
(NO_3-N & NH_4-N) FROM RAINFALL

Although Figure 2 gives only a general estimate of atmospheric nitrogen contributions, some guidelines are available for judging the significance of local conditions. Parameters for these locational variations cannot be identified with sufficient precision to predict the magnitude of a specific influence; however, enough is known from the literature to permit the construction of a matrix indicating the direction of change resulting from identifiable factors. In this manner, Table 19 may be used as a guide for refining local estimations in the absence of direct measurements. Approximately forty factors which influence atmospheric contributions are listed. A "+" sign indicates that the presence of a given condition tends to give higher nutrient inputs via bulk precipitation, a "-" sign indicates lower inputs, and a "0" is used to indicate no effect. A discussion of many of these factors is given by Kluesener (1972).

A comparison of factors listed in Table 19 suggests that atmospheric contributions of both nitrogen and phosphorus are likely to increase in the future. Agricultural and industrial development, activities certain to increase, tend to increase atmospheric nutrient contributions, whereas factors which lead to lower contributions are primarily natural phenomena, not likely to change and generally beyond the control of man. This trend is also supported somewhat by data presented in this report. Of the five study sites where studies were conducted for prolonged periods, higher contributions were detected in later years in all instances. Also, the station of longest continuing record at Ottawa, Canada was abandoned because encroaching industry, intensive agriculture and urban development gave rise to nutrient concentrations higher than those recorded in the past. This may have been the result of truly local influences; however, it may also be indicative of more general trends. Nevertheless, atmospheric contributions of nitrogen and phosphorus appear to be more significant than is generally recognized with respect to control of lake eutrophication, and these contributions are likely to be larger in the future.

Table 19. INFLUENCE OF LOCAL CONDITIONS ON NUTRIENT CONTRIBUTIONS FROM THE ATMOSPHERE

	Influence on atmospheric contribution			
Condition	Nitrogen	Reference	Phosphorus	Reference
1. Existence of intensive agriculture	+	Attshuller '58 Mattson et al '55 Yaalon '64	+	Reimbold et al '67 Carlisle et al '66
2. Animal feedlots and/or high local agricultural animal pop	+	Hoeft '71 Hoeft et al '72 Hutchenson e.a.'69		
3. Industrial activity	+	Firbas '52 Junge '58 Mattson et al '55 Shutt '25 Voigt '60		
4. Urbanization	+	Eriksson '52 Firbas '52 Gorham '61 Shutt '25 Voigt '60		
5. Automobile concentration	+	Harkins et al '67 Myers '70		
6. Power plants and/or explosives factories, fertilizer factories	+	Junge '56 Shy et al '70		
7. Solid waste disposal plants and sites	+	Myers '70		

Table 19 continued. INFLUENCE OF LOCAL CONDITIONS ON NUTRIENT CONTRIBUTIONS FROM THE ATMOSPHERE

Condition	Influence on atmospheric contribution			
	Nitrogen	Reference	Phosphorus	Reference
8. Heavy precipitation in given year relative to previous years	+	Chilingar '56 Chojnacki '64 Daniel et al '38 Matheson '51	+	Allen et al '68 Vijayalakshmi e.a.'62
9. Duration of individual storms	-	Kluesener '72 Angstrom et al '52 Wetselaar et al '63		
10. Predominance of short intense rainfalls	+	Attwill '66 Matheson '51		
11. Frequent presence of fog and dew	+	Eriksson '52		
12. Thunderstorms prevalent	0	Gambell '63 Gambell et al '64 Gambell et al '66 Hutchinson '57 Junge '58 Virtanen '52		
13. Inshore ocean winds	-	Eriksson '52 Gambell '63 Gambell et al '64 Gambell et al '66 Hutchinson '57 Junge '58 Lodge et al '68	-	Reimbold et al '67

Table 19 continued. INFLUENCE OF LOCAL CONDITIONS ON NUTRIENT CONTRIBUTIONS FROM THE ATMOSPHERE

	Influence on atmospheric contribution			
Condition	Nitrogen	Reference	Phosphorus	Reference
14. Turbulent storms (create dust prior to rain)	+	Gambell et al '66 Kluesener '72		
15. Distance inland from major body of water	+	Gambell et al '66 Junge '58 Thornton '65	+	Thornton '65
16. Predominance of snow as form of precipitation	-	Barica et al '71 Herman et al '57 Kluesener '72 Shutt '25		
17. Arid conditions - dry soil	-	Attshuller '58 Junge '58		
18. Tropical conditions	+	Angstrom et al '52	+	Vijayalakshmi e.a.'62
19. Polar conditions	-	Angstrom et al '52 Lodge et al '68		
20. Variations in yearly temperature of soil (highest contributions from warming soils)	+	Allison '55 Yaalon '64		
21. Saturated, poorly areated soil	+	Attshuller '58		
22. High exchange capacity of soils	-	Allison '55		

Table 19 continued. INFLUENCE OF LOCAL CONDITIONS ON NUTRIENT CONTRIBUTIONS FROM THE ATMOSPHERE

Condition		Influence on atmospheric contribution			
		Nitrogen	Reference	Phosphorus	Reference
23. pH of soil	Alkaline	+	Allison '55 Junge '58		
	Acid	-	Kluesener '72 Malo et al '64		
24. Weathered soil, especially prairie		+	Allison '55 Bizzell '43		
25. Soils with high humus content		+	Allison '55 Attshuller '58 Yaalon '64		
26. Tidal marshes				+	Reimbold et al '67
27. Forested areas		+	Tamm '51 Voigt '60	+	Carlisle et al '66 Tamm '51
28. Unpaved roads				+	Reimbold et al '67 Thornton '65
29. Prevalence of grass and forest fires		+	Gore '68 Shutt '25		
30. Heavy bird populations		+	Gore '68		
31. Northern latitude		+	Junge '58		
32. High altitude		-	Junge '58		

REFERENCES

Allen, S. E., A. Carlisle, E. J. White, and C. C. Evans. 1968. The Plant Nutrient Content of Rainwater. J. Ecol. 56:497-504.

Allison, F. E. 1955. The Enigma of Soil Balance Sheets. In: Advances in Agronomy 7. Academic Press, New York, N.Y. p. 231-250.

Angstrom, A., and L. Hoberg. 1952. On the Content of Nitrogen (NH_4-N and NO_3-N) in Atmospheric Precipitation. Tellus 4(1):31-42.

Armstrong, F. A. J., and D. W. Schindler. 1971. Preliminary Chemical Characterization of Waters in the Experimental Lakes Area, Northwestern Ontario. J. Fish. Res. Bd. Can. 28:171-187.

Attshuller, A. P. 1958. Natural Sources of Gaseous Pollutants in the Atmosphere. Tellus 10:479-490.

Attwill, P. M. 1966. The Chemical Composition of Rainwater in Relation to the Cycling of Nutrients in Natural (Mature) Eucalyptus. Plant and Soil 24:390-406.

Barica, J., and F. A. J. Armstrong. 1971. Contribution of Snow to the Nutrient Budget of Some Small Northwest Ontario Lakes. Limnol. and Oceanog. 16:891-899.

Bizzell, J. A. 1943. Comparative Effects of Ammonium Sulfate and Sodium Nitrate on Removal of Nitrogen and Calcium from Soil. Mem. 252, Agr. Exp. Sta., Cornell Univ., Ithaca, N.Y. p. 1-24.

Bizzell, J. A. 1944. Lysimeter Experiments, VI. The Effects of Cropping and Fertilization on the Losses of Nitrogen from the Soil. Mem. 256, Agr. Exp. Sta., Cornell Univ., Ithaca, New York. p. 1-14.

Broadbent, F. E., and H. D. Chapman. 1950. A Lysimeter Investigation of Gains, Losses and Balance of Salts and Plant Nutrients in an Irrigated Soil. Soil Sci. Soc. Amer. Proc. 14:261-269.

Buckman, H. O., and N. C. Brady. 1961. The Nature and Properties of Soils. 6th ed. The MacMillan Co., New York, N.Y. 567 p.

Carlisle, A. A., H. F. Brown, and E. F. White. 1966. The Organic and Nutrient Elements in the Precipitation beneath Sessile Oak Canopy. J. Ecol. 54:87-98.

Chalupa, J. 1960. Eutrophication of Reservoirs by Atmospheric Phosphorus. Fac. Tech. Feul Water 4,1. Inst. Chem. Tech., Prague. p. 295-308.

Chilingar, G. V. 1956. Durvov's Classification of Natural Waters and the Chemical Composition of Atmospheric Precipitation in the USSR: A Review. Amer. Geophys. Union Trans. 37:193-196.

Chojnacki, A. 1964. Nutrient Elements for Plants in Atmospheric Precipitation. Postepy Nauk roln 11:101-112.

Chojnacki, A., and M. Kac Kacas. 1966. Investigations on the Content of Plant Nutrients in Atmospheric Precipitation in the Pulway Region. Roczn Nauk roln 92A:77-89.

Collison, R. C., H. G. Beattie, and J. D. Harlan. 1933. Mineral and Water Relations and Final Nitrogen Balance in Legume and Nonlegume Crop Rotations for a Period of 16 Years. Tech. Bull. 212, Agr. Exp. Sta., Geneva, N.Y. p. 1-81.

Cooke, G. D., T. N. Bhargava, M. R. McComas, M. C. Wilson, and R. T. Heath. 1973. Some Aspects of Phosphorus Dynamics of the Twin Lakes Watershed. In: Modeling the Eutrophication Process. Middlebrooks, E. J. (ed.). Pub. PRWG136-1, Utah Water Research Lab., Utah State Univ., Logan, Utah. p. 57-72.

Daniel, H. A., H. M. Elwell, and H. J. Harper. 1938. Nitrate-Nitrogen Content of Rain and Runoff Water from Plots under Different Cropping Systems on Vermon Fine Sandy Loam. Soil Sci. Soc. Amer. Proc. 3:230-233.

Eriksson, E. 1952. Composition of Atmospheric Precipitation: I. Nitrogen Compounds; II. Sulphur, Chloride, Iodine Compounds. (A Bibliography) Tellus 4:3-4.

Farrugia. 1960. (Unknown. See Vollenweider, 1968, p. 112.)

Finnell, H. H., and H. M. Houghton. 1931. Soil Nitrogen Income from Rainwater. Bull. 23, Pan. Agr. Exp. Sta., Oklahoma.

Firbas, F. 1952. Einige Berechnungen urber die Ernahrung der Hochmoor. Veroff. Geobot. Inst. Zurich 25:177-200.

Freeman, J. F. 1924. Nitrogen in the Rainwater of Different Parts of Kentucky. J. Amer. Soc. Agron. 16:356-358.

Gambell, A. W. 1963. Sulfate and Nitrogen Content of Precipitation over Parts of North Carolina and Virginia. Paper 475-C, U.S. Geolog. Survey. p. C209-C211.

Gambell, A. W., and D. W. Fisher. 1964. Occurrence of Sulfate and Nitrate in Rainfall. J. Geophys. Res. 69:4203-4210.

Gambell, A. W., and D. W. Fisher. 1966. Chemical Composition of Rainfall, Eastern North Carolina and Southeastern Virginia. Water Supply Paper 1535K, U.S. Geolog. Survey. p. 1-41.

Gore, A. J. P. 1968. The Supply of Six Elements by Rain to an Upland Peat Area. J. Ecol. 56:483-495.

Gorham, E. 1961. Factors Influencing Supply of Major Ions to Inland Waters, with Special Reference to the Atmosphere. Geolog. Soc. Amer. Bull. 72:795-840.

Harkins, J. H., and S. W. Nicksic. 1967. Ammonia in Auto Exhaust. Environ. Sci. Technol. 1:751-752.

Herman, F. A., and E. Gorham. 1957. Total Mineral Material, Acidity, Sulphur and Nitrogen in Rain and Snow at Kentville, Nova Scotia. Tellus 9:180-183.

Hoeft, R. G. 1971. Atmospheric Contribution of S and N. Ph.D. Thesis, Soils Dept., Univ. of Wisconsin, Madison, Wis.

Hoeft, R. G., D. R. Keeney, and L. M. Walsh. 1972. Nitrogen and Sulfur Dioxide in the Atmosphere in Wisconsin. J. Environ. Quality 1:203-208.

Hutchenson, G. L., and F. G. Viets, Jr. 1969. Nitrogen Enrichment of Surface Waters by Absorption of Ammonia Volatilized from Cattle Feed Lots. Science 166:514-515.

Hutchinson, G. E. 1957. A Treatise on Limnology, Vol. 1 - Geography, Physics and Chemistry. John Wiley and Sons, New York, N.Y.

Imporato, Gargano. 1964. Ammonia, Nitrate, Nitrite, Phosphate, and Sulphate Contents of Rainwater. Ann. Fac. Agr. Portici 29:369-378.

Ingham, G. 1943. The Fertility of the Air. South Africa J. Sci. 39:35-43.

Jacobson, H. G. M., C. L. W. Swanson, and E. Smith. 1948. Effects of Various Fertilizer Cations and Anions on Soil Reaction Leaching Nitrification of Urea, and Related Characteristics in an uncropped Soil. Soil Science 65:437-460.

Johnson, E. M. 1925. Analysis of Rainfall from a Protected and an Exposed Gage for Sulfur, Nitrate Nitrogen, and Ammonia. J. Amer. Soc. Agron. 17:589-591.

Jones, E. 1960. Contribution of Rainwater to the Nutrient Economy of Northern Nigeria. Nature, London, England 188,432.

Junge, C. E. 1956. Recent Investigations in Air Chemistry. Tellus 8:127-139.

Junge, C. E. 1958a. Chemical Analysis of Aerosol Particles and of Gas Traces on the Island of Hawaii. Tellus 9: 528-537.

Junge, C. E. 1958b. The Distribution of Ammonia and Nitrate in Rainwater over the United States. Trans. Amer. Geophys. Union 39:241-248.

Junge, C. E., and R. T. Werby. 1958. The Concentration of Chloride, Sodium, Potassium, Calcium, and Sulphate in Rain Water over the United States. J. Meteorol. 15: 417-425.

Kluesener, J. W. 1972. Nutrient Transport and Transformation in Lake Wingra, Wisconsin. Ph.D. Thesis, Water Chemistry Dept., Univ. of Wisconsin, Madison, Wis.

Larson, T. E., and I. Hettick. 1956. Mineral Composition of Rainwater. Tellus 8:191-201.

Leland, E. W. 1952. Nitrogen and Sulfur in the Precipitation at Ithaca. Agron. J. 44:172-175.

Lodge, J. P., et al. 1968. Chemistry of the United States Precipitation. Final Rep., National Precipitation Sampling Network, Lab. of Atmospheric Res., Boulder, Colo. 66 p.

Malo, B. A., and E. R. Purvis. 1964. Soil Absorption of Atmospheric Ammonia. Soil Science 97:243-247.

Matheson, D. H. 1951. Inorganic Nitrogen in Precipitation and Atmospheric Sediments. Can. J. Technol. 29:406-412.

Mattson, S., and E. Koutler-Anderson. 1955. Geochemistry of a Raised Bog, II. Some Nitrogen Relationships. Lantbr. Hogsk Ann. 22:219-224.

Myers, P. S. 1970. Automobile Emissions, a Study in Environmental Benefits versus Technological Costs. (January 12-16, 1970) SAE, Automotive Engineering, Detroit, Mich.

Nye, P. H. 1961. Organic Matter and Nutrient Cycles under Moist Tropical Forests. Plant and Soil 13:333-346.

Ottermann, A., and G. Krzysch. 1965. The N, P, K, Ca, and SO_4 Contents of Rain Water in Dahlem. Z. Pflernahr. Dung. Bodenk 111:122-131.

Prince, A. L., S. J. Toth, A. W. Blair, and F. E. Bear. 1941. Forty-Year Study of Nitrogen Fertilizers. Soil Science 52:247-261.

Putnam, H. D., and T. A. Olson. 1960. An Investigation of Nutrients in Western Lake Superior. Sch. of Public Health, Univ. of Minnesota, Minneapolis, Minn.

Reimbold, R. J., and F. C. Daiber. 1967. Eutrophication of Estuarine Areas by Rainwater. Chesapeake Science 8:132-133.

Schraufnagel, F. H. (chrm.). 1967. Excess Water Fertilization Report. Working Group on Control Techniques, Res. on Water Fertilization, Water Subcommittee of Natural Resources Committee of State Agencies, Madison, Wis.

Shah, K. M. 1962. Sulfur and Nitrogen Brought Down in Precipitation in Wisconsin. M.S. Thesis, Soils Dept., Univ. of Wisconsin, Madison, Wis.

Shutt, F. T. 1925. Report of the Dominion Chemist for Year Ending March 31, 1925 (17-year series). Dept. of Agriculture, Domion of Canada. p. 68-74.

Shutt, F. T., and B. Hedley. 1925. The Nitrogen Compounds in Rain and Snow. Proc. Royal Canadian Institute, Ser. IIIA 19:1-10.

Shy, C. M., J. P. Creason, M. E. Pearlman, K. E. McClain, F. B. Benson, and M. M. Young. 1970. The Chattanooga School Children's Study: Effects of Community Exposure to Nitrogen Dioxide. Part I - Methods; Description of Pollutant Exposure and Results of Ventilatory Function Testing. J. Air Pollut. Con. Assoc. 20:539-545.

Shy, C. M., J. P. Creason, M. E. Pearlman, K. E. McClain, F. B. Benson, and M. M. Young. 1970. The Chattanooga School Children's Study: Effects of Community Exposure to Nitrogen Dioxide. Part II - Incidence of Acute Respiratory Illness. J. Air Pollut. Con. Assoc. 20: 582-588.

Sridharan, N. 1972. Aqueous Environmental Chemistry of Phosphorus in Lower Green Bay, Wisconsin. Ph.D. Thesis, Water Chemistry Dept., Univ. of Wisconsin, Madison, Wis.

Sviridova, I. K. 1960. Results of a Study of the Leaching of Nitrogen and Mineral Elements by Rain from the Crowns of Tree Species. Dokl. akad. nauk 133:706-708.

Tamm, C. O. 1951. Removal of Plant Nutrients from Tree Crowns by Rain. Plant Physiol. 4:184-188.

Tamm, C. O. 1953. Growth Yields and Nutrition in Carpets of a Forest Moss. Medd Stat. Skogdforskn. Inst. 43: 1-140.

Taylor, A. W., W. M. Edwards, and E. C. Simpson. 1971. Nutrients in Streams Draining Woodland and Farmland near Coshocton, Ohio. Water Resources Res. 7:81-89.

Thornton, I. 1965. Nutrient Content of Rain Water in Gambia. Nature 205:1025.

Vijayalakshmi, K., and K. M. Pandalai. 1962. Nutrient Enrichment of the Coconut Soils of the Humid Kerala Coast through Monsoon Precipitation. Nature 194:112.

Virtanen, A. I. 1952. Molecular Nitrogen Fixation and the Nitrogen Cycle in Nature. Tellus 4:304-306.

Voigt, G. K. 1960. Distribution of Rainfall under Forest Stands. Forest Science 6(1):2-10.

Voigt, G. K. 1960. Alteration of the Composition of Rainwater by Trees. Amer. Midland Nat. 63:321-326.

Vollenweider, R. A. 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication. Reference DAS/CSI/68.27, Organisation for Economic Cooperation and Development, Directorate for Scientific Affairs, Paris, France.

Weibel, S. R., R. J. Anderson, and R. L. Woodward. 1964. Urban Land Runoff as a Factor in Stream Pollution. J. Water Pollut. Con. Fed. 36:914-924.

Weibel, S. R., R. B. Weidner, J. M. Cohen, and A. G. Christianson. 1966. Pesticides and Other Contaminants in Rainfall and Runoff. J. Amer. Water Works Assoc. 58:1075-1084.

Wetselaar, R., and J. T. Hutton. 1963. The Ionic Composition of Rain Water at Katherine N.T. and Its Part in the Cycling of Plant Nutrients. Australian J. Agr. Res. 14:319-329.

Whitehead, H. C., and J. H. Feth. 1964. Chemical Character of Rain, Dry Fallout, and Bulk Precipitation at Menlo Park, California, 1957-1959. Geophys. Res. 69(16): 3319-3333.

Wilson, B. D. 1921. Nitrogen in the Rain Water at Ithaca, New York. Soil Science 11:101-110.

Woodruff, C. M. 1949. Estimating the Nitrogen Delivery of Soil from the Organic Matter Determination as Reflected by Sanborn Field. Soil Sci. Soc. Amer. Proc. 14:208-212.

Yaalon, D. H. 1964. The Concentration of Ammonia and Nitrate in Rain Water over Israel in Relation to Environmental Factors. Tellus 16:200-204.

SUMMARY

It is apparent from the data tabulated in this report that considerable variation exists in the quantities of nutrients that are exported from "similar" areas devoted to the same use. In considering the contributions of nutrients from diffuse sources, and considering the flow of water to be the primary transport mechanism, it would be expected that important contributing factors would include:

1. General topography, particularly contour.

2. Precipitation characteristics, including: total annual amount; seasonal distribution; duration, frequency and intensity of storms; and snowfall/runoff.

3. Soil properties, including: chemical exchange characteristics, mineral composition, grain size distribution, antecedent soil moisture, and hydraulic properties such as permeability.

4. Vegetative cover, including: type, density and permanence.

5. Manipulative practices, such as paving, plowing, flooding, and fertilizing.

6. Animal populations--type and density.

Other factors could also be identified, but of those listed, only the latter three groups relate directly to land use. Although topography, precipitation, and soil characteristics influence to some extent the use which is made of particular lands, these factors generally do not impose restrictions that severely limit the range of possible uses. Therefore, land use designations do not account for these parameters, and additional studies are needed to develop techniques for including them in the estimation procedure. This could be accomplished by refined subdivision of drainage areas and the measurement of corresponding nutrient loss or, possibly, by the development of guidelines for selecting appropriate nutrient flux coefficients which incorporate these parameters in addition to land use information.

Those data most applicable for estimating nutrient loadings from non-point sources are listed below and referenced to tables included in the previous sections.

Contributions from:	Tables	Pages
Diffuse sources:		
agricultural lands	9	36-38
urban areas	11	49
forested lands	13	58
wetlands and marshes		60-61
Groundwater transport		62-68
Bulk precipitation	17 & 18	79-84
Miscellaneous:		
manure handling		40-42
animal populations	10	41
septic tanks		71-72

Based on the results of nutrient transport studies reported here, there appears to be little justification for the delineation of land usage within direct drainage basins beyond four categories: urban, forested, agricultural, and wetlands. With one possible exception--agricultural lands, the available data are too fragmentary and variable to warrant further specification of use categories. Armstrong et al (1974) estimated that on the basis of surface runoff studies, agricultural lands could be further subdivided and thet the following flux coefficients might be considered "average" values.

	Nitrogen loss, kg-N/ha/yr		Phosphorus loss, kg-P/ha/yr	
	NO_3+NH_4	Total-N	Diss Inorg	Total-P
Row crops	1.6	37.	0.21	1.62
Close-grown crops	1.7	15.	0.13	0.47
Pasture & meadow	2.3	2.5	0.22	0.24
Idle (fallow) land	3.9	67.	0.05	1.23

after Armstrong et al (1974)

The coefficients for the soluble inorganic nutrient forms compare reasonably well with corresponding values determined from streamflow studies. However, the coefficients for runoff of total N and total P are much larger than those determined by streamflow studies, and the usefulness of these data for purposes of estimating lake loadings is questionable.

Nutrient runoff values for urban, forested and agricultural areas (streamflow studies only) are plotted in Figures 3b, 3c and 3d, respectively. Figure 3a is a plot of the baseline conditions and key, which are used to provide a perspective for the runoff data. Throughout the discussion which follows, only diffuse sources of nutrients are considered; atmospheric input is ignored; and it is assumed that drainage basins are devoted to only one use.

The abscissa for all plots is nitrogen export from watershed areas in kg/ha/yr; ordinate values are the ratio of nitrogen export/phosphorus export. The plotted data points refer to paired values of dissolved inorganic phosphorus and nitrate plus ammonia-nitrogen (open circles) or total phosphorus and total nitrogen (solid circles).

For discussion purposes, the plots are subdivided by horizontal and radial lines. The horizontal lines define areas where $N/P > 15$, $15 > N/P > 10$, and $N/P < 10$. Based on the nutritional requirements of algae, it might be expected that algal populations in lakes which receive nutrient loadings with $N/P > 15$ would tend to be phosphorus-limited. Conversely, if $N/P < 10$, nitrogen limitation might be expected. Obviously, this is a gross simplification which applies to lake environments in only a cursory way; but the concept is used here to illustrate some of the differences and similarities of runoff waters from lands of various use categories.

The radial lines on the plots are based on a "permissible" specific lake loading rate of 1.5 g-N/m^2/yr and 0.1 g-P/m^2/yr (these rates are equivalent to 15 kg-N/ha/yr and 1.0 kg-P/ha/yr). Each radial line refers to a given ratio of direct drainage basin area/lake surface area, and lines for ratios of 1, 3, 5, 10, and 50 are shown. Data points which lie to the right (clockwise) of any radial line refer to loading rates which would exceed both permissible loading limits given above; points to the left of any radial line refer to loading rates which are less than these limits.

For example, the open data point in Figure 3a corresponds to nutrient flux coefficients of about 3 kg-N/ha/yr and a coefficient ratio, N/P, of about 23 (i.e., a phosphorus loss of about $3/23 = 0.13$ kg-P/ha/yr). The location of the point on the plot indicates that flux coefficients of this magnitude would result in permissible loading rates in those situations where basin areas are only 5 times as large as the receiving lake; but the permissible loading limit would be exceeded if the basin areas are 10 or more times as large as the lake.

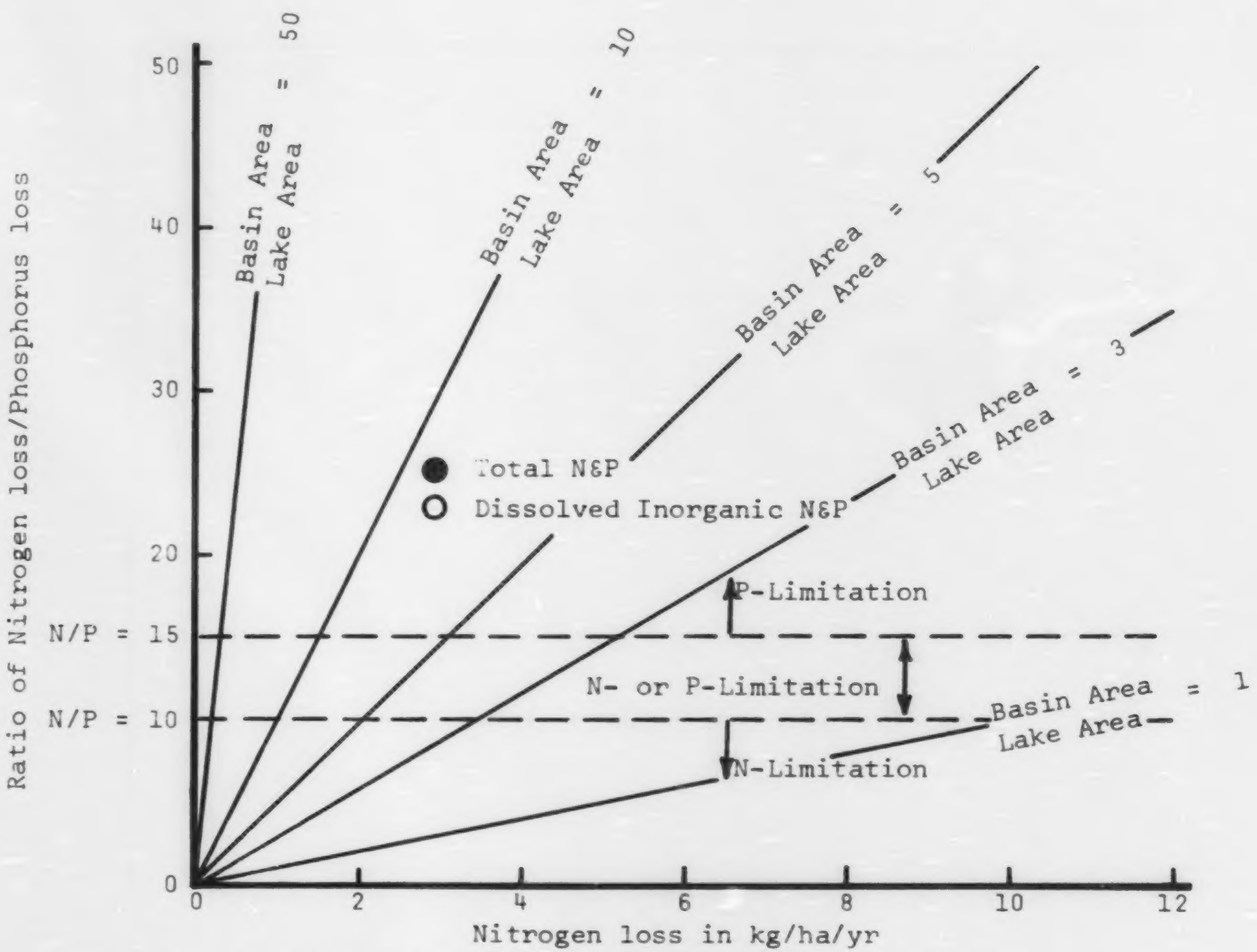

Figure 3a. FORMAT FOR COMPARING NUTRIENT RUNOFF COEFFICIENTS

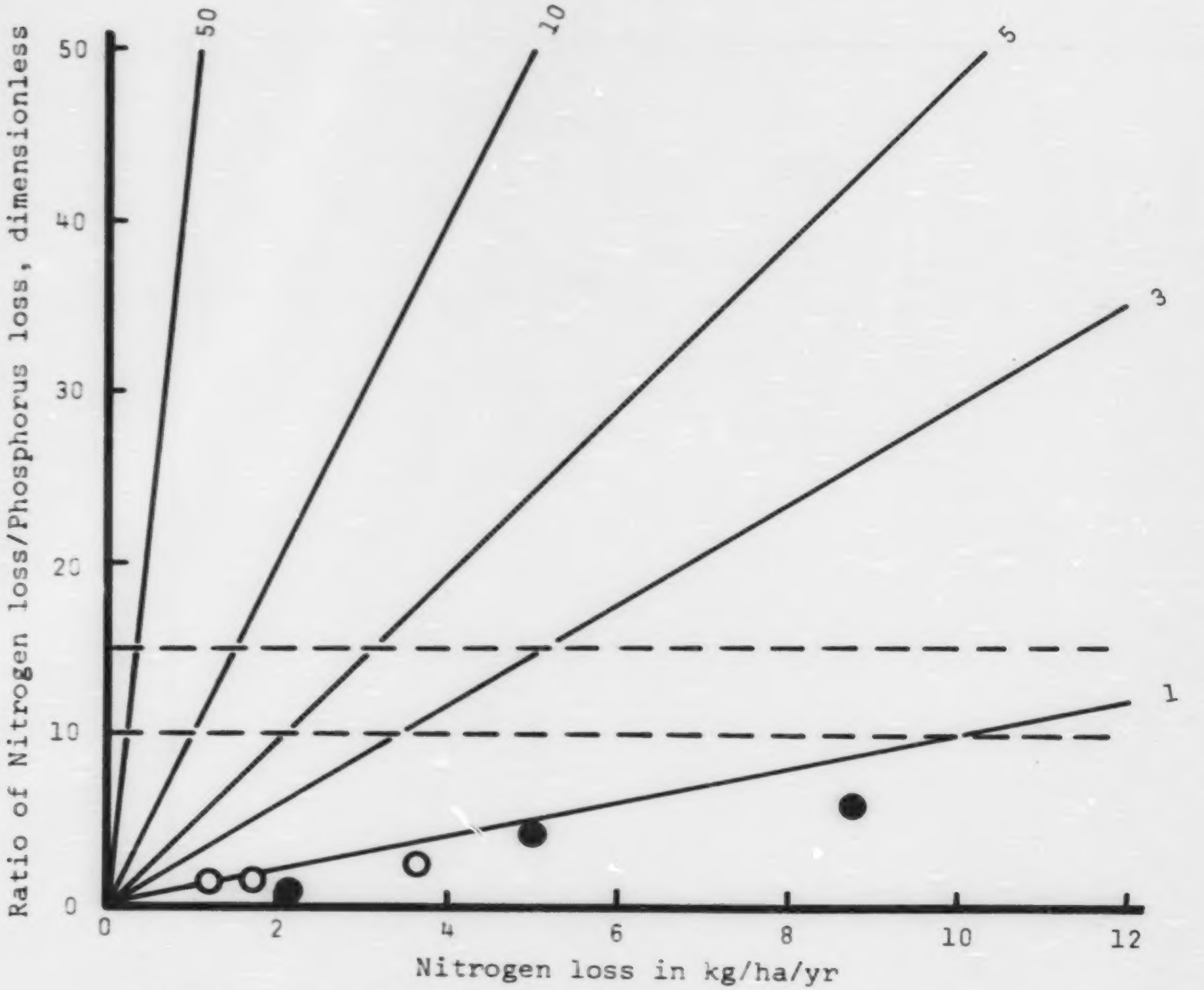

Figure 3b. NUTRIENT EXPORT FROM URBAN AREAS

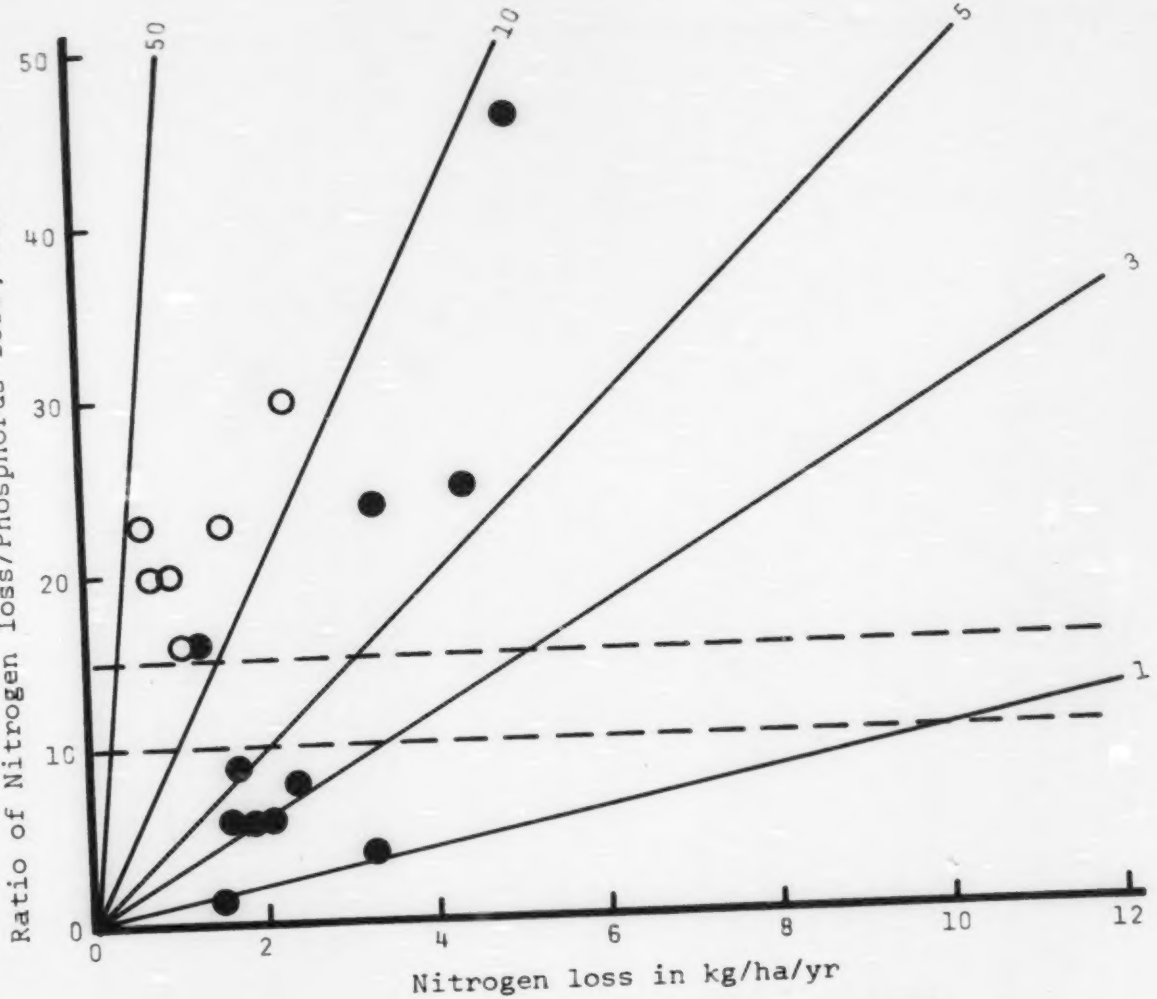

Figure 3c. NUTRIENT EXPORT FROM FORESTED LANDS

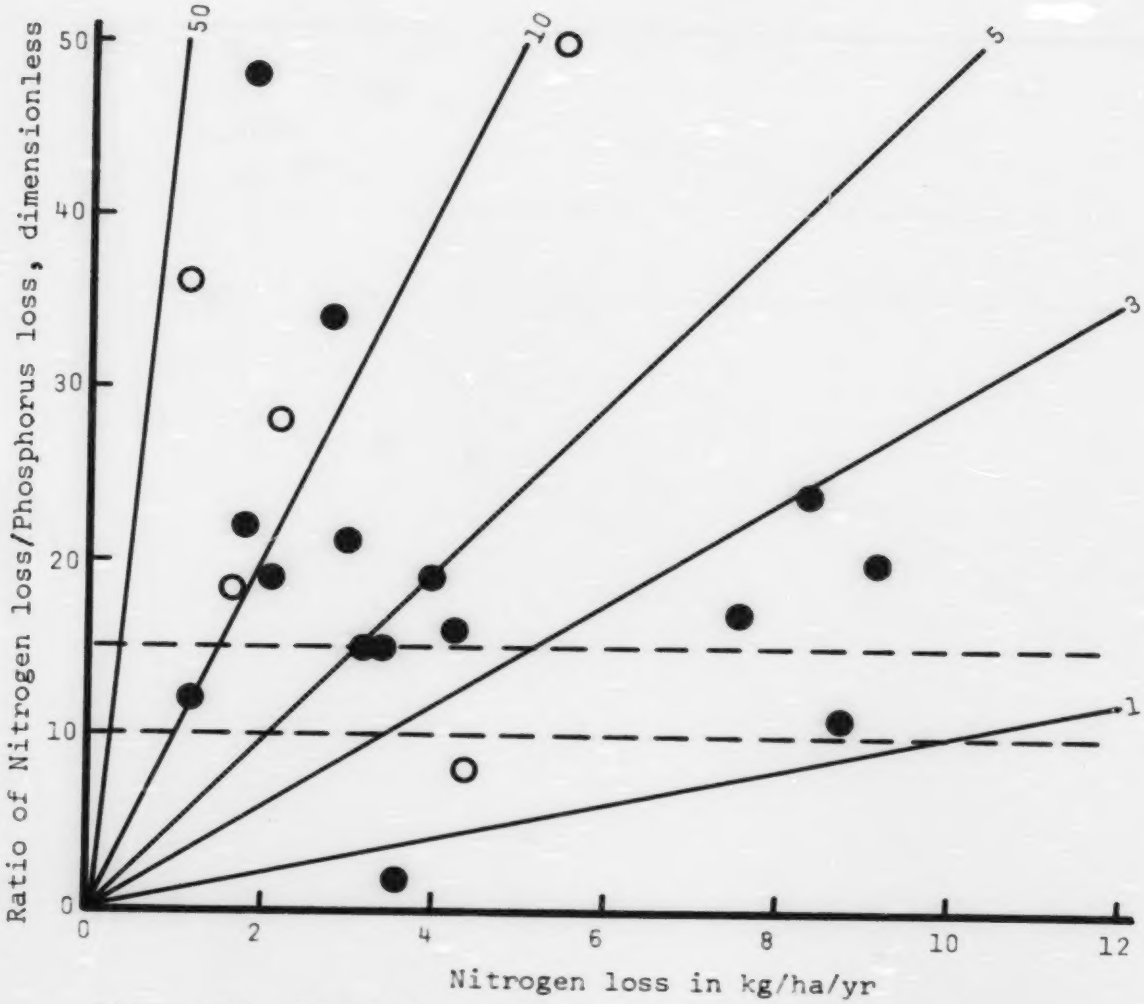

Figure 3d. NUTRIENT EXPORT FROM AGRICULTURAL LANDS

In addition, the runoff would be relatively rich in nitrogen so that there may be a tendency toward phosphorus limitation in the receiving waters.

Runoff coefficients for urban areas are plotted in Figure 3b. Although only six data points are available, this plot dramatically illustrates the very fertile nature of urban runoff. Not only is this runoff very high in phosphorus on a relative basis, it is also high in both nitrogen and phosphorus in absolute terms. Very small drainage areas--basin-to-lake area ratios of unity or less--are sufficient to provide excessive amounts of nutrients.

In comparison, nutrient runoff from forested lands (Figure 3c) is far less intense. Considering only dissolved inorganic nutrient forms, runoff from forested areas would not approach the specified loading limit unless the drainage area was more than 10 times as large as the lake and, in some cases, area ratios as large as 40 would not cause excessive loadings. It is interesting to note that the soluble inorganic constituents of forest drainage are high in nitrogen relative to phosphorus, whereas the opposite is true for the majority of cases when total nutrient forms are considered.

A greater degree of variability is shown by the data from agricultural drainage studies (Fig. 3d). On a relative basis, most studies showed that agricultural drainage was high in nitrogen. Considering only soluble inorganic nutrient forms, basin/lake area ratios as small as 2 or as large as 40 resulted in nutrient runoff values that approached the permissible limit specified.

Table 20 gives nutrient flux coefficients which might be considered to be high, low, or average values. These values were obtained by averaging and comparing available coefficients without regard to geographical location. Thus, the specification of high or low values is relative to the other numbers in the data set, and these numbers do not necessarily apply to all portions of the country. For example, the average runoff coefficient given for dissolved inorganic phosphorus from agricultural lands is 0.1 kg/ha/yr. However, for the upper Midwest, it would be expected that the "average" runoff coefficient would be much closer to 0.5 kg/ha/yr, the high value listed in Table 9.

It is apparent that nitrogen export from diffuse sources is far less variable than phosphorus runoff. Ignoring land use categories, flux coefficients for total nitrogen vary by a factor of 10, and soluble inorganic nitrogen values vary by a factor of 20. In comparison, corresponding values for phosphorus vary

Table 20. TYPICAL VALUES OF NUTRIENT RUNOFF COEFFICIENTS

Land use	NO_3-N+NH_4-N kg/ha/yr High	Low	Ave	Total-N kg/ha/yr High	Low	Ave
Urban	5.0	1.0	2.0	10.0	2.5	5.0
Forests	3.0	0.5	1.6	5.0	1.0	2.5
Agricultural	10.0	1.0	5.0	10.0	2.0	5.0

	Diss inorg-P kg/ha/yr High	Low	Ave	Total-P kg/ha/yr High	Low	Ave
Urban	2.0	0.5	1.0	5.0	1.0	1.5
Forests	0.1	0.01	0.05	0.8	0.05	0.2
Agricultural	0.5	0.05	0.1	1.0	0.1	0.3

by factors of 100 and 200. However, variation within land use categories is smaller--nitrogen values vary by factors of about 5; phosphorus values vary by factors of 10.

The high and low runoff coefficients can be used to define ratios of drainage basin area/lake area for which 1) permissible loading levels would almost certainly be exceeded (low coefficient) and 2) ratios for which loadings would almost certainly be less than permissible limits (high coefficients). Using the same permissible loading levels as above--1.5 g-N/m^2/yr and 0.1 g-P/m^2/yr--and considering only dissolved inorganic nutrient forms, this approach yields the following extreme ratios of basin area/lake area for which:

	NO_3-N+NH_4-N loading would be: below limit	above limit
Urban	3	15
Forests	5	30
Agricultural	1.5	15

	Dissolved inorganic phosphorus loadings would be: below limit	above limit
Urban	0.5	2
Forests	10	100
Agricultural	2	20

To place these values in perspective, basin area/lake area ratios for some of the larger lakes in Wisconsin are given in Table 21. Of the 26 lakes listed, 6 had area ratios larger than 15, and 4 had area ratios less than 5.

Table 21. DIRECT DRAINAGE AREAS FOR SELECTED WISCONSIN LAKES[a]

Name	County	Lake area ha	Basin area km^2	$\frac{\text{Basin area}}{\text{Lake area}}$ (dimensionless)
Impoundments:				
Mason L	Adams	347	60	17
Arbutus	Clark	332	16	5
L Wisconsin	Columbia	3640	319	9
Beaverdam L	Dodge	2240	339	15
Fox L	Dodge	858	98	12
Sinissippi	Dodge	930	109	12
St Croix	Douglas	774	41	5
Menomin	Dunn	599	23	4
Tainter	Dunn	709	65	9
Flambeau	Iron	5481	298	5
Gile Flow	Iron	1369	137	10
High Falls	Marinette	606	41	7
Buffalo	Marquette	990	1557	158
Willow Flow	Oneida	2078	246	16
Balsam L	Polk	769	282	36
Chequamegon	Taylor	1105	44	4
Natural lakes:				
Bear	Barron	544	21	4
Namekagon	Bayfield	1298	34	3
Big Sand	Burnett	567	21	4
L Mendota	Dane	3938	650	17
Kegonsa	Dane	1099	62	6
Waubesa	Dane	855	220	26
Kangaroo	Door	445	47	10
Franklin	Forest	361	78	22
Big Green	Green L	2964	287	10
Bone	Polk	678	31	5

[a] Based on Wisconsin Department of Natural Resources lake inventory data.

The potential significance of atmospheric contributions of both nitrogen and phosphorus were discussed previously. In some parts of the United States, particularly in the Great Lakes

Region, these contributions may be large and, also, in situations where basin area/lake area ratios are small, bulk precipitation may provide the majority of the nutrient input.

Nutrient content of rainfall and dry fallout has been receiving a considerable amount of study during the past few years, and additional study results are continually appearing in the literature. The data listed here are rapidly becoming obsolete and should be viewed as a summary of older studies. An attempt should be made to locate recent data applicable to the area in question (particularly for phosphorus) before resorting to the data listed in this report.

Few generalizations can be made regarding nutrient input to lakes via groundwater, other than to point out the highly variable nature of groundwater communication with lakes and the potential for sizable nutrient contributions--phosphorus as well as nitrogen--in some situations. At the present time, it appears that site-specific information is a necessity for estimating the exchange of water between lakes and surrounding aquifers and, even when flow rates are known, the poorly-defined role of bottom sediments as nutrient exchange media and sites for nutrient transformations greatly complicates estimation of nutrient influx.

Hydrologic and chemical complexities of wetland areas have, for the most part, prevented the establishment of nutrient budgets for wetlands. It appears that some wetland areas act like "capacitors" which store nutrients for release at a later time but, on an annual basis, there is no net storage or release of nutrients. Until such time as the loading criteria for lakes include consideration of the timing of nutrient inflow, flux coefficients for wetlands should probably be assumed to be zero.

Considering the present state of knowledge, the estimation of nutrient loadings to lakes is as much an art as it is a science. The selection of appropriate flux coefficients is critical; a wide range of values is possible; and guidelines to aid in the selection of runoff coefficients are lacking. Consequently, management decisions based on estimated loadings must be balanced against the inherent degree of uncertainty associated with the technique. This uncertainty cannot be described in terms of an "accuracy of ± x%," but the limitations of the technique can be evaluated in a management context.

The estimation of nutrient loadings is a logical first step in the development of almost any water quality management plan for lakes, because it forces the identification of potentially significant nutrient sources and provides a measure of their relative importance. Based on this information, and in consideration of practical constraints and opportunities which exist, tentative management plans can be specified. For example, these plans might include a program of nutrient abatement for the contributing watersheds. At this point, the adequacy of the estimated loadings can be evaluated. If the elements of the management plan are sensitive to the flux coefficients used in the loading estimate, i.e., if the use of slightly different flux coefficients would lead to the conclusion that a different management approach should be followed, then the limitations of the estimation technique have been exceeded and site-specific field evaluation would be necessary. If not, it may be possible to rely on the estimated loadings and eliminate, or at least reduce, the need for extensive field monitoring and evaluation.

In all probability, the practice of estimating nutrient loadings of lakes will be expanded in the future. The lack of comparable alternatives almost assures that increased reliance will be placed on this approach. The technique has limitations which must be recognized but, despite its shortcomings, it can be a valuable decision-making tool.

REFERENCE

Armstrong, D. E., K. W. Lee, P. D. Uttormark, D. R. Keeney, and R. F. Harris. 1974. Pollution of the Great Lakes by Nutrients from Agricultural Land. Great Lakes Basin Commission, Ann Arbor, Mich. 96 p.

Table 12. CONVERSION FACTORS

acres	x 0.405	=	ha	x 2.471	= acres
mi^2	x 259	=	ha	x 0.00386	= mi^2
m^2	x 10^{-4}	=	ha	x 10^4	= m^2
km^2	x 100	=	ha	x .01	= km^2
lbs	x 0.454	=	kg	x 2.205	= lbs
ton	x 907.2	=	kg	x .0011	= ton
lbs/acre	x 1.12	=	kg/ha	x 0.892	= lbs/acre
ton/mi^2	x 3.5	=	kg/ha	x 0.286	= ton/mi^2
ton/acre	x 2242	=	kg/ha	x 0.000446	= ton/acre
lbs/mi	x 0.00176	=	kg/ha	x 569.8	= lbs/mi
acre-ft	x 1233.5	=	m^3	x 0.00081	= acre-ft